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MINERAL NUTRITION OF PLANTS AND ANIMALS

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BY

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To OLE A. NELSON

PREFACE

DURING THE PREPARATION of a series of mineral-nutrition experiments conducted at the Battelle Memorial Institute, it became apparent that a literature survey both of specific problems and of the entire field was required. The valuable bibliography of Willis, with its supplements, and the works of Miller and of Beeson, each of which required years of preparation, were used as a starting point. However, it was seen from the first that, even with the available background, a complete coverage of such an extremely broad subject would be encyclopedic, and a complete bibliographical summary of all nutritional research with its medical applications would be a herculean task, requiring years of effort.

Time-consuming works of such size, important as they might be, were not feasible. However, there did appear to be a need for a lesser effort concerning the reviews and more important papers dealing with mineral nutrition that would cover the subdivisions of the subject sufficiently to serve as a foundation for more intensive search in restricted fields. It was with this objective that the following comprehensive study was prepared.

A large part of the literature dealing with nutrition is concerned with domestic animals and cultivated plants, and practically all of this can be considered in terms of human nutrition. The need for improving the quality of our food becomes apparent to anyone interested in this or any other study dealing with the subject of nutrition. However, it seems that the practical side of nutrition has lagged far behind the theoretical. A problem has been created, and a certain amount of the literature now deals with the economics of making the public aware of the desirability of consuming food of higher quality.

FRANK A. GILBERT

Columbus, Ohio

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MINERAL NUTRITION OF PLANTS AND ANIMALS

I. INTRODUCTION

ANIMALS AND PLANTS have certain chemical needs, those of animals being supplied by the plants on which they feed. Thus the plant is the great intermediary by which certain elements of the rocks, after their conversion into soil, are assimilated and made available to animals and man. The simple inorganic constituents of the atmosphere and the soil are selected and built up by the plant into complex organic substances which may be further elaborated, with selection and removal of elementary components by the animal, into flesh, blood, bones, and other structural materials.

There are marked differences between the elementary composition of the soil and that of plants or animals. Plants have the faculty of assimilating large amounts of certain elements out of proportion to their abundance in the soil, and animals have a similar but less pronounced ability to screen out certain elements from the plants. The ability of plants to absorb minute amounts of needed elements, while keeping out larger amounts of unnecessary ones, is perhaps best illustrated by marine algae such as *Laminaria*, in whose ash is found an abundance of potassium but little sodium, although sea water contains these elements in the reverse proportions. Likewise, the ratios of calcium in the mineral elements of soils, plants, and man are approximately 1:8:40, those of phosphorus 1:140:200, and those of sulfur 1:30:130, respectively (53[1]).

It is also significant that the two most abundant mineral elements of the earth's crust—silicon and aluminum—are found only in traces in the bodies of men and animals. Animals require comparatively large amounts of sodium and chlorine and traces of iodine and cobalt, but it has never been demonstrated that these elements are necessary for the life of a plant. On the other hand, boron and molybdenum are essential to plants but not to animals.

[1] Numbers in parentheses refer to entries in the bibliography, which begins on page 101.

The proportion of an element in the ash of a plant is not indicative of that element's relative value to the plant, for the percentage of silicon or sodium, neither of which has ever been proved to be absolutely essential, may be far greater than the percentage of boron, copper, or other elements without which the plant cannot develop normally.

Up to the present time, approximately sixty elements have been positively identified in plants (257), many, of course, in extremely small quantities; and it is possible that all known elements, excepting perhaps the rare gases, may eventually be found in plants, given sufficient material for analysis together with analytical methods of greater sensitivity. This does not mean that all plants contain traces of this number of elements but merely shows that an individual plant may be capable of taking in elements present in the soil, even though they are not necessary to its development.

Before the soils of a large part of this country had been exploited and much of their fertility taken off or washed into the streams, there was little opportunity for mineral deficiencies to appear. It is true that some soils were less fertile than others; but, as long as nothing was removed, what mineral content there was remained and was continuously available. Now the situation has changed, and we are becoming increasingly aware that our soils are being drained of their more soluble minerals. This is most apparent in the sandy eastern and southern soils—not only because they were exploited at an earlier date, but also because they are more readily leached than the heavier soils to the west.

The luxuriance of a plant is not necessarily a criterion of its nutritive value or its mineral content, and the usual commercial fertilizer may or may not add to a deficient soil all that is needed. The caloric value and the nutritional value of a plant cannot be considered in the same light, for livestock may develop marked symptoms of disease on mineral-deficient but apparently fertile soils.

We have a serious nutritional problem today, of which we are but recently aware and which we might call "hidden hunger." This problem will have to be solved if we are to retain our present standard of living.

One authority on soil science at a recent meeting of biologists suggested, as a solution, a greater consumption of foods originating

from more widely scattered sources. Successful as this plan might be for the relatively few persons who can afford to obtain all their food from more newly established sources, it does not solve the problem, since most of the plant food produced is consumed near the farms on which it is grown. The question remains: How can we obtain nourishing food for ourselves and our livestock from the land already in use?

With so many thought-provoking problems on hand, and with such a volume of literature, it is natural that a considerable number of very complete bibliographies or reviews on the microelements and their relation to nutrition should have been prepared (35, 51, 176, 254, 298a, 317, 321).

A number of less inclusive surveys have also been made of the role of minerals in nutrition, centering around the mineral requirements of plants and animals (49, 50, 105, 129, 153, 159, 180, 194, 206, 211, 214, 218, 256, 328). One of the most recent and important of these (111a) stresses papers on the behavior relationship of soil, nutrition, and health.

II. EARLY HISTORY OF PLANT NUTRITION

NUTRITION, like many other branches of science, may be traced back to Aristotle (21). His belief that a plant, like an animal, took in food "already elaborated" was accepted until comparatively recent times. So great was Aristotle's prestige that few men had the audacity to challenge his concepts for many centuries, greatly to the detriment of scientific progress.

Aristotle taught that the food of both plants and animals was not simple but was composed of various combinations of what were then thought to be the four elements: earth, air, fire, and water. Plants, however, not having organs for rendering their food suitable to their purposes, took in nutrients peculiarly adapted to them and, since this food was already elaborated, produced no excrement as animals did. Experimentation apparently was not considered or was believed beneath the dignity of the great men of that day, and the chief point of contention was the method by which the "nutrient fluid" was circulated through the plant. One method suggested by

Cesalpino (62) was the power of suction. As a sponge attracts moisture, so was the plant believed to convey "nutrient fluid" from the earth into itself.

Bernard Palissy (233), in the sixteenth century, was possibly the first to question Aristotle's view, for he made several practical observations on the importance of salts in the nutrition of plants; but his work was largely overlooked or not considered seriously in his time.

Van Helmont (311), in the seventeenth century, attempted to prove by his classic and often quoted experiment that the whole substance of plants was formed from water alone. In this experiment, a 5-pound willow was planted in 200 pounds of dry earth, and rain water, only, was added as needed. After five years, the tree was found to weigh 169 pounds, 3 ounces, while the earth, again dried and weighed, was found to have lost only 2 ounces.

To determine whether the water itself or what it contained in the way of dissolved matter was the nutrient material used by plants, Woodward (325), in 1699, grew spearmint, potatoes, and vetch in water from a conduit, and in river and spring water, as well as in rain and distilled water. His conclusion was that the water was the carrier of the necessary terrestrial matter.

Malpighi (196), in 1687, called attention to the leaves as organs of nutrition but apparently never considered the possibility of a synthetic process taking place there, believing, rather, that the nutrient sap was changed in the leaves by fermentation through the warmth of the sun's rays. The fact that the sun's rays, rather than the heat derived therefrom, were essential to the growing plant was apparently not demonstrated until 1740 by Mariotte (198), although the possibility was suggested some years earlier by Hales (122), who explained the circulation of the sap by capillarity and transpiration through the leaves. It was surmised also at this time, although not proved, that green leaves were capable of absorbing gases.

This was as far as the physiologists of the time were able to go until Black, in 1754, discovered "fixed air," rechristened "carbonic acid" by Lavoisier in 1781; Priestley discovered "dephlogisticated air" or "oxygen" in 1774; and Lavoisier showed that water is composed of hydrogen and oxygen. Priestley observed that living plants were able to convert air "injured" by the burning of candles or the

breathing of animals into healthful air, and concluded that plants reverse the effects of breathing.

About the same time that Priestley was making these observations, Scheele (267) was arriving at exactly opposite conclusions. He found that germinating peas, instead of purifying air, converted a part of it into "aerial acid," just as animals do. These apparently anomalous results, easily understandable today, were due, of course, in part to the failure of Priestley to recognize the difference between the behavior of green and nongreen parts of the plant, and in part to a lack by Scheele of a proper appreciation of the importance of sunlight.

Shortly after Priestley's first observations were made known, Jan Ingenhousz started investigations on the subject. In his first book (151) he was able to explain the differences in the results of Priestley and Scheele, but apparently he did not have any conception that the "foul air" absorbed by the plant contributed to its sustenance. In the meantime Lavoisier had shown that carbonic acid contained carbon and oxygen and that water was composed of hydrogen and oxygen, thus freeing Ingenhousz from the phlogiston concept with which science had been handicapped to that time. Now, according to the newer chemistry, he knew that "fixed air" was a compound of carbon and oxygen, and had little difficulty in his second book (152) in putting forward a comprehensive theory of plant nutrition, so far as the plant's relation to air was concerned. His findings, which we hold as true today, were that green shoots give off oxygen in sunlight and carbon dioxide in darkness but that nongreen parts give off carbon dioxide at all times.

At the same time that Ingenhousz was pursuing his researches, Senebier was also experimenting with the influence of light on vegetation. According to Spoehr (292), one line of attack, original with Senebier, was the determination of the fraction of light which was most active in photosynthesis.

We owe the first satisfactory quantitative studies of the fundamental facts of photosynthesis to De Saussure (82), who demonstrated that a green plant cannot live without some carbon dioxide. He undertook to determine the amount of carbon dioxide which, mixed with air, is most favorable to vegetation and arrived at 8.3 per cent in direct sunlight. His percentage is interesting because it

is precisely that found by Godlewski and by Kreussler seventy and eighty years later. De Saussure succeeded in proving that plants growing freely in the air and, given pure water, obtain their carbon from the small amount of carbon dioxide normally present in the atmosphere. The fixation of water by plants takes place only coincidently with the fixation of carbon, and oxygen is liberated only as a consequence of the decomposition of carbon dioxide. He also concluded that plants are dependent on the nitrogen of the soil, and his belief was confirmed almost a half-century later by Boussingault (45).

In spite of the findings and deductions of De Saussure, the "humus theory of nutrition" still persisted—its advocates maintaining that plants, like animals, utilized carbon in the organic form, obtaining it from partly decomposed animal and vegetable matter in the soil.

It remained for Liebig (170) to put an abrupt end to this speculation by proving that, on the basis of its insolubility, humic acid, even under the most favorable conditions, could not contribute more than a small fraction of the carbon found in the plants grown on the land. Liebig stated: "Plants live upon carbonic acid, ammonia (nitric acid), water, phosphoric acid, sulfuric acid, silicic acid, lime, magnesia, potash, and iron," and showed that nitrogen is taken in through the roots as ammonium salts or nitrates.

The earlier theories of plant nutrition are more or less completely covered in most histories of botany (251) or chemistry (213) and in a fragmentary manner in many texts on plant physiology (214). One of the most comprehensive of recent reviews was that of Sherman (274), which appeared in 1933.

III. CLASSIFICATION OF THE ELEMENTS USED IN NUTRITION

A. *Essential* vs. *Unessential Elements*

Up to 1927 (234), thirty-five elements had been detected in the analysis of plants, and ten of these were known to be necessary for plant growth. Those of us first exposed to chemistry in the early twenties can hardly fail to remember the sentence "C HOPKNS

CaFe Mg (mighty good)" quoted by the instructor for the purpose of impressing these ten elements on the minds of the unresponsive students.

Up to the present time approximately sixty elements (257) have been positively identified in plants, of which more than one-third are conceded to be essential for either plant or animal nutrition, with a few more on the probable list. An analysis will show that the bulk of a green plant is composed of a relatively small number of elements, the "big four" or energy elements—carbon, oxygen, hydrogen, and nitrogen—making up approximately 95 per cent of the dry weight, and the major ash elements—phosphorus, potassium, calcium, magnesium, silicon, aluminum, and sodium, plus sulfur and chlorine—making up most of the remainder. The so-called trace elements account for 1 per cent or less of the total weight, except in unusual cases or in some accumulator plants, which may absorb unusually large amounts of certain elements, for example, selenium, aluminum, or silicon.

The amount of an element in a plant or animal must not be considered a criterion of its relative value, for some elements present in very small quantities are as essential to growth as those which compose the greater portion of the plant or animal.

The number of elements in a plant is determined by their presence in the soil and air. The amount or proportion depends on many factors: species, age, and root distribution of the plant, physical and chemical nature of the soil, proportion and distribution of the elements, methods of cultivation, and general climatic conditions. In an animal, however, the most important single factor is the food which the animal consumes, along with any feeding supplement such as salt.

Thatcher (301) proposed a classification of the chemical elements according to the functions in the metabolism of the green plant as follows: (1) hydrogen and oxygen—energy-exchange elements; (2) carbon, nitrogen, sulfur, and phosphorus—energy storers; (3) sodium, potassium, calcium, and magnesium—translocation regulators; and (4) manganese, iron, cobalt, nickel, copper, and zinc—oxidation-reduction regulators. The other elements were placed into four other groups, but their functions in the plant were not suggested.

Some elements are essential to both plants and animals in greater or lesser amounts; some are essential to one or the other; and some are of probable, but at present uncertain, value to either or both. For example, sodium is most essential for animals but, although frequently present and able to replace potassium to a limited extent in plants, has never been proved to be necessary to them, as plants can be grown to maturity without it. On the other hand, potassium is one of the plant macronutrients, but somewhat less valuable to animals. Carnivorous animals obtaining sufficient sodium from the flesh on which they feed apparently do not crave this element. Herbivorous animals, lacking a sufficient amount in their food, receive it as a supplement, and in the wild state may travel great distances to obtain it from a spring or lick.

Molybdenum has recently been shown to be necessary to plants (22) but has been known to be toxic to animals when more than a trace is present(102). Cobalt is essential to the well-being of animals but never has been proved necessary to the growth of plants (225). Aluminum, although found in both plants and animals, is not considered to be essential to either, since all attempts to produce aluminum deficiency have been negative(149).

There is some question about what constitutes biological essentiality of an element. Presence in a plant or an animal does not constitute essentiality. Proof of an indispensable nutritive function of a chemical element is now considered as afforded only through nutritional experimentation. Steinberg (296) states: "Positive results imply that the diet is proportioned and just adequate for maximum normal growth if the element is added, and unsatisfactory if omitted, and that other elements of similar chemical properties cannot be so employed." In living plants and animals, enzyme action may not be the same in the field and in the laboratory. Frequently several elements may serve to activate an enzyme. It should not be assumed, therefore, that the organism has to employ the most efficient of these in its nutrition. Even the formation of metabolites of an element is not a criterion of its essentiality if the organism is capable of dispensing with it, as, for example, chlorine in certain fungi.

The proof that biological specificity need not constitute biological essentiality may be illustrated by the presence of sodium in green plants. This element may replace potassium to some extent in the

nutrition of the plant, whereas lithium and caesium are unable to do so. Nevertheless, sodium is not essential to green plants or to fungi, according to Steinberg, since either can apparently thrive without it. A nutritive chemical element, therefore, is one whose reduction in the diet results in decreased growth, structural abnormality, and possibly death of an organism, depending on the degree of deficiency, and whose total omission makes it impossible for the organism to exist.

Deficiencies in trace elements or micronutrients, as in macronutrients, are in all cases reflected by a diminution of yield or growth and—if the deficiency is extreme—by morphological abnormality. The few parts per million or billion of the micronutrients, therefore, are as important as the far larger quantities of macronutrients the plant or animal also requires. The value of the micronutrients in the past has been lost sight of in the laboratory because only recently have highly refined methods of eliminating traces of these from the macronutrients been developed. Nutrition depends on vitamins as well as mineral nutrients and energy foods; and, although this discussion is not designed to include the voluminous literature on the vitamins, their importance makes it necessary to mention them in connection with mineral nutrients.

There has been relatively little work dealing with the relation between mineral nutrition of plants and their vitamin content. Recent reviews by Maynard and Beeson (207), Hamner and Maynard (125), and Hamner (124) have covered much of the literature in the field. These reviews have indicated that variations in the vitamin content of plants are related to many factors, including varietal differences, climatic and seasonal differences, and, to a much less extent, differences in the degree of fertilization. The evidence concerning the influence of fertilizer practices and soil factors is not conclusive. Fortunately, from a practical standpoint, the treatments which are likely to give the highest crop yield per acre are also the ones most likely to give the highest vitamin yield per acre.

B. *The Energy Elements*

Carbon, oxygen, hydrogen, and nitrogen compose approximately 95 per cent of the dry weight of a plant. The carbon is practically

all obtained from the air in the form of carbon dioxide. The hydrogen and a considerable portion of the oxygen are obtained from the water absorbed by the plant. The remainder of the oxygen is obtained from the atmosphere. Therefore, except under desert conditions where water is the limiting factor, these three elements are present in abundance and need not be considered further in plant or animal nutrition. All other elements that enter a plant must be presented to it in the form of soluble compounds.

According to the amount necessary for proper nutrition, nitrogen is the most important element taken in by plant roots. It enters into the structure of the chlorophyll of plants and into the structure of the amino acids, amides, alkaloids, proteins, and protoplasm as they are found in plants or animals. It occurs for the most part in organic combination, and the percentage will vary with age, type of tissue, and kind of plant or animal, as well as the period of day when the examination is made.

An abundance of nitrogen in plants produces a lush growth of foliage and, if present in inordinate amounts compared to other elements, causes a rank and succulent vegetative growth at the expense of reproduction. In the absence of sufficient nitrogen, a yellowing soon occurs and the leaves become stunted, the older ones drying out and dropping off.

One of the most striking differences in the metabolism of animals and plants is that the former continually excrete nitrogen compounds, while the latter rarely if ever do so. The nitrogenous compounds eliminated by animals are chiefly urea, uric acid, and ammonia, which, along with other compounds, result from the breaking down of proteins and protoplasm. The same compounds are apparently formed in the life processes of the plant cell, but are again directly utilized in the formation of new protein compounds and are not eliminated as in animals. However, nitrogen is lost when plants are burned or when the discarded leaves and other parts are leached by runoff water. Nitrogen compounds are so soluble that nitrogen is one of the most easily leached of the elements and, therefore, is one of the most important constituents of fertilizers.

Unlike nonvolatile elements in the soil, nitrogen tends to accumulate, provided it is not exploited by the removal of crops without return in the form of fertilizer and there is sufficient organic and

colloidal matter to keep it from leaching out faster than it can accumulate. Although the amounts vary, it has been estimated that five to seven pounds per acre annually are brought down by the rain, about twenty-five pounds are added by nonsymbiotic soil organisms, and about eighty pounds are added by symbiotic legume bacteria (272).

The nitrogen in the soil may vary more from farm to farm in one locality, or even from field to field, than in different sections of the country, although the prairie soils of the Midwest have always averaged a much higher nitrogen content than the forest soils of the East. The red and yellow southern soils, possibly because they are sandier and because organic matter is held with greater difficulty, have a much lower average nitrogen content.

The nitrogen content of a soil is more the result of an accumulation of the element after the formation of the soil itself than a basic part of the original rock. In addition, any deficiency of the element is quickly apparent in the growth and color of the plants growing on the soil. Because of these conditions, no hidden diet deficiencies connected with a certain area or type of soil are due to a lack of nitrogen.

However, where livestock are fed on a low protein diet, or where economic restrictions force families to live almost exclusively on carbohydrates, or where certain customs and habits tend to make protein consumption inadequate, the lack manifests itself in stunted growth and unsatisfactory reproduction and rearing of young. General ill health, mental and physical inefficiency, fatigue, lack of resistance to infection, and other ill effects have also been cited as results of protein deficiency in the diet. A serious and prolonged deficiency of protein produces an edema or dropsy that was fairly common in Europe during the world wars and has been known to occur among poor people in this country. Because of these results of deficiency, it is especially important that growing children and pregnant and lactating women have a liberal amount of protein.

c. *The Macronutrient Elements*

Although the minerals compose only about 5 per cent of the body of mammals and green plants and less than 1 per cent of the weight of protoplasm, they take a disproportionately large part in the body

metabolism of both plants and animals. Numerous investigations have shown that the normal physiological activities are not possible in the presence of protein, carbohydrates, fats, and water alone. Even though these energy-yielding constituents may be present in abundance, yet the tissues are incapable of performing their functions unless the required mineral elements are added.

Of the mineral elements, phosphorus, calcium, magnesium, potassium, sulfur, and sodium and chlorine are sometimes called the "macronutrients"—not because they are more important but because they are necessary in somewhat greater amounts than others. The first five are essential to both plants and animals, and the last two to animals alone.

When there is even a slight lack of phosphorus in the diet, normal animal growth is prevented. Plants differ greatly in their need for phosphorus, some plants being able to grow on soils quite deficient in this element. Needless to say, animals forced to obtain their food almost entirely from these deficient plants will soon show symptoms of phosphorus deficiency.

Calcium is present in the body in a larger amount than any other mineral element. The skeleton is the normal storage place for calcium, very little being found in the other tissues. However, the small fraction not present in the skeleton is important in determining the state of health of the body. Calcium is essential to the growth of all plants except the fungi and some of the lower algae, but the amount in a plant varies greatly with the species and with environmental conditions. Animals feeding on plants grown in soil with a low calcium content or on plants naturally low in this element may be unable to satisfy their calcium requirement unless given supplementary food rich in this bone-forming mineral.

Knowledge of the importance of magnesium in nutrition has lagged far behind that of the other inorganic elements that are present in the body to any considerable extent. In 1932 it was conclusively demonstrated that magnesium is a nutritional essential for animals (167). It is usually present in the plant in somewhat smaller amounts than calcium; but, since it is a constituent of chlorophyll, its deficiency in the plant is visible as a pronounced chlorosis. Magnesium deficiency in a plant is not common; therefore, a specific deficiency in animals is unusual.

Potassium is essential for plants and cannot be entirely replaced by any other elements. Apparently it can be absorbed from the soil in any soluble inorganic form; and, while exploited soils become depleted in available potassium, the requirements of animals for this element are so low comparatively that their food usually contains an ample amount to meet their needs.

It has long been recognized that sulfur is necessary for plant and animal life, but the amount needed by plants was underestimated until recently. A general survey of the sulfur and phosphorus contents of crop plants and soils reveals the fact that soils in general are more deficient in sulfur than in phosphorus. However, sulfur has been applied more or less unwittingly with phosphorus in fertilizers, the sulfur content frequently exceeding the phosphorus content. The atmosphere contains a considerable quantity of sulfur compounds which are brought down by rains and function in the nutrition of plants, so that a soil that is not heavily cropped gradually builds up its sulfur content. For these two reasons sulfur deficiencies have not appeared frequently. As sulfur is a constituent of protein, it is present quite generally in vegetable and animal matter. Plants are believed to be able to form proteins from inorganic sulfates, but animals cannot. Therefore, animals must obtain their sulfur from the animal and plant proteins which they consume. When the protein intake is adequate, sulfur intake is not a nutritional problem.

The requirements of sodium and chlorine are not ordinarily defined separately. These elements are usually taken into the body at the same time in the form of sodium chloride and are excreted together. Both are generally found in plants, where sodium may replace potassium to a slight extent, but neither has been proved to be essential to plant life. The tissue of a normal human adult contains about sixty grams of sodium. When vegetable intakes are high, sodium chloride is particularly needed, for it is in the medium of the sodium ion and the chloride ion that the vital actions of digestion take place.

Sodium occurs chiefly in the body fluids, and is stored for the most part in the skeleton and muscles. About one-third of the total chlorine content of the body is present in the skin and the tissue under it. It has been demonstrated that life cannot be supported and normal

growth cannot take place when the sodium intake is too low (263). However, no human diet, even without added salt, contains so little sodium that it cannot support life.

D. *The Micronutrient Elements*

Of the "micronutrient" minerals, iron, copper, zinc, and manganese are necessary to both plant and animal life. Boron, molybdenum, silicon questionably, and possibly gallium are deemed necessary to plants but not to animals, while cobalt and iodine are necessary to animals but have never been proved to be essential to plants. Aluminum and fluorine, although found in both plants and animals, are of questionable necessity for either.

Iron is an essential constituent of plant and animal protoplasm. Although the amount of iron present in animals is small, it is of vital importance in the living processes concerned with the transport of oxygen and the metabolism of food material within the cell. A deficiency of iron or its impaired utilization in the body causes anemia. Plants quickly show a lack of iron by a chlorosis of the younger parts but are capable of taking in more than the minimum amount necessary when it is obtainable. Seldom are soils actually deficient in this element, but several factors may make it relatively unavailable to plants and hence to animals feeding exclusively on these plants.

Zinc, like iron, is found in all tissues and foodstuffs. It is indispensable in animal nutrition because of its growth-promoting properties and its presence as a constituent of insulin crystals. Because of the small amount necessary, there appears to be little danger of a zinc deficiency in the average animal diet, but there have been several reported cases of plant malnutrition in zinc-deficient soils.

Although it had been known for some time that copper occurred in plant and animal tissues, no physiological function was assigned to it until 1928 (133), when the element was proved to be necessary as a supplement to iron in the formation of hemoglobin. Anemic animals fed on forage from copper-deficient soils have been aided by the addition of a small amount of copper to the diet. Although it has been proved that copper is essential to the growth of plants (288, 289), there is as yet little knowledge concerning its role in plant metabolism.

Manganese is present in all plants and animals and is an essential element in nutrition. It has been suggested that the function of manganese in the animal may be concerned with the development of the pituitary gland and the regulation of the sex glands. Rations low in manganese produce a condition that interferes with normal lactation and induces a high mortality rate in the young, and a still greater reduction prevents reproduction entirely. A lack of manganese in plants results in a poor development of chlorophyll and in oats causes a deficiency disease known as "gray speck." Some areas of soil are deficient in manganese and, therefore, produce crops inferior in quantity as well as in food quality.

From the standpoint of agriculture, boron is unique among the chemical elements in that very small quantities are necessary for the normal growth of plants, and only slightly higher concentrations cause injury. With a number of plants, the range between these two levels in water culture is only a few parts per million. There are several well-known deficiency diseases of agricultural crops caused by a lack of this element. It appears to function in the development of the meristem tissue, for the terminal buds are usually the first parts of the plant that manifest abnormality resulting from a shortage. At present there is no certain knowledge of its value, if any, to animals.

Silicon is an element that is found in all higher plants, but the amount varies greatly in different plants and in different parts of the same plant. The large amounts present led early to the belief that it might be an essential element in plant nutrition. It has been shown, however, that plants which normally contain large amounts may be grown to maturity in nutrient solutions that have only a trace. At present, therefore, although the need for silicon in plant growth seems apparent, attempts to purify or recrystallize chemicals in order to eliminate all traces of the element have not been too successful, and it has not been proved either that silicon is absolutely necessary or that plants can grow without it.

Evidence that a soil can become deficient in molybdenum is scanty; yet there are some observations which suggest that it is not invariably supplied by soils to plants in amounts sufficient to meet the full physiological needs of the crop. The necessity of molybdenum for growth in some plants has been proved, but its physiologi-

cal function in these plants is not completely known. It is not essential for animal nutrition.

Gallium has been shown by Steinberg (295) to be necessary for the growth of the fungus *Aspergillus niger* but has not been demonstrated to be essential to green plants or to animals.

The lack of cobalt in the diet of herbivorous animals has been the cause of an anemia known by various names, depending on the part of the world in which it occurs. This anemia can be prevented or cured by adding cobalt to the soils in which the forage is grown or including traces in the feed of the affected animals. The element has been found in extremely small amounts in most of the organs of the animal body and is known to increase the number of red corpuscles in the blood. The exact relation of iron, copper, and cobalt to anemia is incompletely understood, and some anemia cases that are not helped by one of these elements alone respond to a combination of all three. Cobalt, although present in traces in all plants except those growing in deficient regions, is not necessary to plant growth.

The public is perhaps more aware of the value of iodine than of any other micronutrient, with the possible exception of iron, because of its role in the prevention of goiter and cretinism. Most of our knowledge concerning the human requirement for iodine is based on the estimation of the iodine intake and excretion of people in nongoitrous and goitrous regions. Plants vary considerably in the amount of iodine present, which is more or less proportionate to the amount in the medium in which they grow. Most plants contain measurable to large amounts of iodine, but the fact that they can be grown to maturity without this element proves that it is not essential to their metabolism.

Because aluminum has been found in all plants and animals, its value to them has been a matter for considerable investigation. Thus far, however, it has never been proved to be essential, as both plants and animals appear to be able to develop normally without it. At one time considerable interest centered around the possible toxic effects that might occur from the use of aluminum cooking vessels and baking powders containing aluminum; but rather extensive studies have shown no evidence of aluminum poisoning in amounts in excess of those which would ordinarily be ingested.

Arsenic, lead, and selenium are usually considered in the light of their possible toxic effects on plant and animal life, rather than for any value they might have as micronutrients. There is some evidence that arsenic has a function in animal nutrition, but lead and selenium are not considered to have any beneficial effect on either plants or animals, even as traces. The selenium absorbed by some plants has been shown to aid them by discouraging or killing insects sucking the juices, but this indirect benefit is a matter of insect toxicity rather than of plant stimulation.

The value of the individual elements to plants, animals, and human beings will be enlarged upon in the following chapters; and the more important works, including reviews, will be cited, so far as they refer to these elements.

IV. PHOSPHORUS

A. *Phosphorus in Plants and Animals*

VILLE (312) seems to have been one of the first to show that phosphorus was necessary for plant growth. Although his experiments were performed with sand cultures, they showed such definite results that there could be no doubt of his conclusions. He also showed that in order to serve as a plant nutrient, the phosphorus must be in the phosphate form.

The amount of phosphorus in plants ordinarily ranges from 0.2 to 0.8 per cent of the total dry substance but is lower than this in plants grown in deficient soils. It is present in somewhat greater quantities than sulfur and magnesium and in smaller quantities than calcium. A considerable amount (from 50 to 80 per cent) of the phosphorus in plants is soluble in water—a fact which, if generally known, should make farmers less prone to let their hay become rain soaked, or housewives less eager to boil vegetables and pour away the water in which they were cooked.

The phosphorus in plants occurs in greater amounts in seeds and fruits than in the rest of the plant, and the total content in the tissues depends upon the amount in the soil. Jordan (161) has shown that, up to a certain point, the production of plant substance increases with the increased phosphorus supply but that, beyond this, phos-

phorus is not utilized in increased plant growth. In some areas, where livestock "does poorly," both legumes and grasses grow luxuriantly and apparently provide liberal amounts of minerals other than phosphorus (90). It may thus be seen that it is possible for plants to make a good vegetative growth and yet be deficient both in the production of seed and as forage for animals. Livestock may starve for phosphorus or other mineral elements in the midst of apparent plenty.

Plants receiving sufficient phosphorus show a steady increase in amount from the bottom of the plant to the young growth at the top but, when receiving little phosphorus, have approximately the same per cent in all regions of the stem and leaves (89). This seems to indicate that the element has a property of distribution somewhat greater than most other elements in the plant.

Plants absorb and utilize phosphorus, for the most part, in the form of phosphates, but they can to a limited extent utilize some organic phosphorus (271). The amount in the sap of a plant generally varies directly with the amount in the soil, so that by heavy applications of phosphorus to the soil a proportionate increase of this element in the plant usually may be obtained (203), although this is not always the case (56, 187, 241, 314). The necessity of phosphorus to both plants and animals is unquestioned; and in plants, phosphorus is one of the component elements of several organic compounds including phytin, phospholipides, hexose phosphates, nucleic acid, and probably phosphoproteins (214).

The distribution of body phosphorus in a mammal reveals that 70 to 80 per cent is present in the skeleton, 10 per cent in the muscles, and 10 per cent in the nervous system. Because phosphorus is an essential component of every cell, the remaining fraction is widely distributed. The requirement of the growing animal is relatively high, and the minimum requirement for the adult man averages about 0.88 grams per day, merely to replace the loss from the body (323).

B. *Phosphorus Deficiency in Soils and Crops*

Phosphorus has been called the master key to agriculture. Its importance in general farming is indicated by the fact that low crop

production is due more often to a lack of phosphorus than to a deficiency of any other element. Practical experience by farmers and the many experimental trials conducted on different soils by various state experiment stations have shown that most soils respond to additions of phosphatic fertilizer (90, 314). The only marked exceptions are the soils of a few places such as the bluegrass regions of Kentucky and Tennessee, which were formed from rocks high in phosphorus, both total and available, and a few locations where certain factors inhibit the availability of the phosphorus. Among these factors may be hydrogen ion concentration, moisture relations, calcium supply, and organic matter. Large amounts of iron and aluminum make phosphorus unavailable in very acid soils, and there is some evidence that too high a calcium content where the pH of the soil is 7.5 tends to produce a similar effect (187,241). Phosphate fertilizer increased the phosphorus content of *Lespedeza* by 40 per cent in one soil but by only 17 per cent in another (314). In the Florida area (259), one soil, because of its high phosphate-fixing power, required comparatively large applications of fertilizer to increase the phosphorus content of the forage.

As might be expected, a wide difference is found in the deficiency of phosphorus in various soil types. In general, acid clay soils, low in organic matter, give more response to phosphorus fertilizers than other soils of the same region. In many cases, however, the extent of phosphorus deficiency is determined not by the soil type but by the treatment the soils have received since they were brought under cultivation. Phosphorus deficiency becomes evident after land is farmed for a few years, especially under a grain or livestock system of farming. It is not surprising, therefore, that the soils in the eastern and southern United States showed the need of phosphorus first, and that most of the phosphorus, as well as other fertilizers, have been used in this general section.

It should not be inferred that phosphorus is not needed in other parts of the country. Experimental work in recent years has established the need for phosphorus, almost without exception, in soils that have been cropped over a period of years, including the fertile soils of the Great Plains region. The lack in the soils of the United States generally is evidenced by the large amount of phosphatic fertilizers applied. They make up approximately half of the tonnage

Phosphorus deficiency in tomato seedlings

Seedling A shows a purplish coloration on the lower surface of the leaves, an early symptom of phosphorus deficiency.

Seedling B is not deficient and is approximately the same size as the deficient seedling, although several days younger.

of materials used in mixed fertilizers and half of the separate fertilizers bought by farmers. The practice of using bones or fish for improving the productivity of the soil is so old that there is no record of its origin, but, of course, the reason for the benefit by the bones or fish was not understood.

Although the total amount of phosphatic fertilizers used on American farms has been steadily increasing, the amount used per acre is still very small compared to that which is needed. Fortunately, because the United States is the chief producer of superphosphate, the farmers of this country have available a relatively cheap source of supply.

The phosphorus content of soils differs greatly. In many of the sandy soils of the Atlantic and Gulf coastal plains, the amount of phosphorus in the plowed layer is less than five hundred pounds per acre. On the other hand, the fertile Brookston soils of Ohio and Indiana average more than five times that amount (240).

The phosphorus content of the soil may be low not only because of low original amounts but also because of cropping and grazing; and there have been great losses as the result of soil erosion. Schollenberger in Ohio (270) and Whitson and Stoddard in Wisconsin (320) determined that in fifty years the land cropped for grain in these two states lost about one-third of its total phosphorus. Even in livestock farming, the phosphorus recovered through the manure and reapplied to the soil only delays the loss to some extent, as six carloads of cattle may contain phosphorus equivalent to that in the surface six inches of soil on an acre of land, and the milk from a dairy of 130 average cows will carry off this quantity of phosphorus every year (303). Lipman and Conybeare (175) estimated that the amount of phosphorus lost annually through erosion was approximately equal to the amount estimated to be removed each year by grazing and harvested crops.

It is well understood that there are large areas in various countries throughout the world where serious losses among grazing animals occur because the forage is abnormally low in phosphorus on account of soil conditions. The low phosphorus content of herbage appears to be more frequently the result of soil conditions which render the phosphorus unavailable than an absolute deficiency. On the other hand, marked differences in total phosphorus content may be primary factors.

In the central basin of middle Tennessee there are extensive soil areas developed from a phosphatic limestone which are recognized as unusually fertile soils (314). Some of these are said to contain as much as 6,200 pounds of phosphorus pentoxide and 6,400 pounds of calcium oxide per acre to plow depth. In contrast, the Highland Rim surrounding the basin consists of poor nonphosphatic soil with only 1,000 pounds of phosphorus pentoxide and and 3,200 pounds of calcium oxide per acre. There is a marked difference in the phosphorus content of hay grown on certain soils in the two areas. For example, *Lespedeza* cut in early bloom on Maury silt loam in the basin contained 0.27 per cent phosphorus, whereas the same type of hay cut at the same stage from Clarkesville silt loam in the poor areas contained only 0.1 per cent. Animals fed on the basin hay made 50 per cent better gains than those fed on the rim hay.

In areas in Florida where phosphorus-deficiency troubles have

Phosphorus-deficiency symptoms in tomato leaves

Note the prominent veins, reddish-purple in color, and the pale lower side of the undersized leaves, characteristic of phosphorus deficiency.

been reported, the phosphorus content of the foliage is correlated with the water-soluble phosphorus present in the soil (56).

It is a common observation that phosphorus-deficiency troubles are more severe in times of drought, and that in borderline situations they may occur only in dry seasons or dry years. Daniel and Harper (75) found that the phosphorus content of grasses and legumes grown on various soils correlates with the amount of rainfall—that the lighter the rainfall, the smaller the amount of this element in the forage (91).

Certain plant species tend to take over land depleted in phosphorus and other minerals. They are of value in helping to prevent erosion but are avoided by grazing animals if more nutritious herbage is available. When pastures containing such species are fertilized with phosphates, the better plants, such as bluegrass and clover, tend to crowd out the poorer types, such as *Aristida* (poverty grass) and *Andropogon* (beard grass). Although the plants of the poorer types are also benefited, it is to a lesser degree, and the better species with an accelerated growth soon surpass the others.

It has been found that to obtain optimum yields of most crops, a much larger amount of phosphorus must be applied than is eventually removed in the first year's crop. This is because some of the phosphorus combines with the soil, that is, is "fixed," and is not immediately available. This is a process of great practical importance, for it determines the efficiency of phosphorus fertilizers on different soil types. Under ordinary conditions, not more than about 20 per cent is recovered in the first crop, but a part of the remainder is recovered in subsequent years, although little data concerning percentage are available. In a Missouri pasture it was found that cattle still showed a preference for a section that had been fertilized with calcium and superphosphate six years before (11). In a pasture experiment in West Virginia (240) the application of superphosphate exerted a marked effect four and one-half years later, not only on the yield and type of vegetation but also on the phosphorus content of the herbage.

c. *Phosphorus Deficiency in Livestock*

Of all mineral deficiencies of livestock, phosphorus deficiency is probably the most common and widespread. It has been reported from at least twenty states (34, 84, 90, 91, 104, 128, 135, 136, 146, 179, 186, 255, 259, 269, 315), as well as from Canada (190), the British Isles (93), many sections of Europe (231), South America (87, 144), South Africa (302), Asia (181), Australia (201, 246), and New Zealand (25). The deficiency occurs more frequently in cattle than in other stock, presumably because in certain sections they receive little food except that grown in deficient soils.

In dairy cows the deficiency causes failure and depravement of appetite, stiffness, and muscular weakness, in addition to loss of weight. Good recovery is noted when phosphates are added to the diet. One form of depravement of appetite is bone chewing, the result of the animal's effort to satisfy its craving for phosphorus (130, 146, 315). Where depraved appetite, or "osteomalacia," a disease of the bones (also colloquially known as "sweeny," "creeping sickness," "loin disease," or "down in the back") occurs, the soil of the locality and the forage obtained from it will be deficient in phosphorus or calcium, or both (49).

Courtesy Florida Agricultural Experiment Station

A cow affected by "stiffs" or "sweeny," the direct result of a diet low in phosphorus, caused by pasturage on land deficient in that element. Note the emaciation, stiffness, and general unthrifty appearance of the animal.

Cases of acute phosphorus deficiency in herbivorous animals are not limited to range or pasture feeding. They can occur in barn or lot feeding when the roughage has come from an area typically low in phosphorus and is fed without a sufficient supplement of foods richer in this mineral. Dove (84) found that there were chronic deficiency diseases of cattle in Maine because the soils were naturally low in phosphorus and calcium, more than 80 per cent of the dry forage was nonleguminous, and 96 per cent of the forage was home grown.

Extreme deficiencies are immediately detected, but the more numerous borderline cases often pass as normal. In the improved dairy animal the amounts of phosphorus and calcium required for milk production are usually so high that, even if the forage is but slightly deficient, the milk yield will decrease. Later the animal will gradually lose weight, will fail to breed, or breed with difficulty, and eventually physical degeneration will occur.

Leguminous crops make more satisfactory rations than nonleguminous ones, but on fertile soils timothy and other nonleguminous hays furnish good mineral nutriment (212). On the other hand, even legumes, when grown on deficient soils, may not supply sufficient minerals for the animals unless the diet is supplemented with bone or grain high in the deficient elements (145).

Although it is not a major factor compared to the amount of available minerals in the soil, the intensity of the light does have some effect on the amount of phosphorus and calcium deposited in plant tissue. During cloudy weather and in periods of low light intensity, many forms of plant life are affected by the lack of ultraviolet and fail to deposit normal quantities of these bone-forming minerals in the plants (297). In coastal regions, where fogs are prevalent and the essential mineral content of the soil not too great. this factor may have considerable effect.

Courtesy Missouri Agricultural Experiment Station

Troubles during pregnancy that suggest milk fever long before calving

This cow was pastured on green grass growing on deficient soil. In terms of nutritive value of the forage, animal "troubles" can be traced to the fertility of the soil. Bulk of a crop is not necessarily the full measure of its value as feed.

Courtesy Missouri Agricultural Experiment Station
Photograph by W. A. Albrecht

This donkey had a fine pedigree, but that didn't prevent his bone troubles when, as a colt, he was moved from one soil region of Missouri to another that grows a big bulk of crop but evidently does not provide proper nutrition.

Slight deficiencies are slow or lagging in their effects. It has been reported that on phosphorus- and calcium-deficient pastures, sheep and cattle of Wales do not grow to full size but remain stunted (84); and horses pastured on the mineral-deficient soils of the Falkland Islands became smaller with each generation, gradually reverting to the size of ponies.

An interesting observation has been made by Welch (315) on the effect of restricted grazing on the nutritional health of western livestock. When ranges were free, cattle roamed about to pick and choose the grasses needed for health; but fencing and the resulting confinement prevented this free choice of pasture to satisfy the nutritive instinct. As a result, those animals confined to areas in which the soils and crops were deficient became deficient themselves. Albrecht has shown (5, 11) that animals have an extremely fine sense

of discrimination between good and deficient forage, and will not eat the latter so long as any of the minerally sufficient food is available.

In suggesting remedies for phosphorus deficiency in beef cattle, Black and associates (40) mention supplementing the diet with bone meal or with dicalcium or disodium phosphate. The first has the advantage of being more palatable to the cattle. Dove (84), in recommending methods of preventing deficiencies of livestock in Maine, mentions, in addition to the mineral supplement of bone meal in the feed, the feeding of fish meal, a method practical only where it is accessible in quantities, or the addition of cod-liver oil to the feed. The latter would make more available the phosphorus and calcium already present. For example, the addition of cod-liver oil would not be so efficient in Nebraska as in Maine, since Nebraska has 15.7 per cent more sunlight hours than Maine and is 5 degrees farther south. However, a mineral supplement is not necessary where the pastures are kept in productive condition by proper fertilization practices.

The subject of phosphorus and other mineral deficiencies of animals has been reviewed several times in the past few years (36, 84, 105, 132, 136, 144, 205, 206, 302, 317), and material containing references to phosphorus deficiency is voluminous.

D. *Summary*

Phosphorus, more than any other element, is the cause of low crop production, and the amount used on American farms is only a fraction of what is needed for the best results. The pastures and hayfields of the United States are especially in need of phosphorus, because most of them have never been fertilized, although cropped continuously for many years. Presumably this situation is due to failure to recognize the importance of pastures in a permanent system of farming and to the mistaken conception of some farmers that "hay is hay" regardless of where it was produced.

For many years there has been a continuous removal of phosphorous from hay lands and pastures, until the reduced mineral content has resulted in many pastures that support only poor species of plants of low quality which, pound for pound, are much less valuable than better species. Animals grazing on this deficient forage and

not receiving supplementary food richer in minerals eventually show evidences of malnutrition.

One outstanding problem is to convince the farmer and the public that a deficiency of phosphorus, and other elements as well, does not become apparent through a great decrease in the volume of forage produced but, instead, may be evidenced by a malnutrition of the animals feeding on the minerally deficient forage.

V. CALCIUM

A. *Calcium in the Plant*

CALCIUM is one of the most important of the biological mineral elements and is necessary to the growth of all animals and all green plants, with the exception only of some of the lower algae. It is not necessary for the development of the fungi (296). The first demonstrations concerning the necessity of this element for the growth of plants are supposed to have been carried out by Salm-Horstman in 1856 (264) and, according to Reed (250), by Stohman in 1862, who, by cultivating corn plants in solutions lacking calcium, found that the leaves died at the tips but that the plants recovered quickly with the addition of a small amount of the element.

Calcium is believed to have several functions in the plant, although some of these have been a matter of controversy. Loew (178) ascribed a highly important function to calcium, regarding it as one of the important mineral bases which enter into the constitution of the proteins composing the cell nucleus and plastids. According to his interpretation, these proteins take up magnesium in the absence of calcium, and the resulting magnesium-protein compound has not the same well-defined capacity of inbibition which the calcium-protein bodies possess; hence the harmful effects observed when plants are grown in a calcium-free medium containing magnesium. Lipman (172), however, after having reviewed the subject, concluded that there was no more reason to assume that there should be a proper calcium-magnesium ratio in the soil than that there should be a proper ratio between calcium and any other essential element.

Moser (220) could find no significant correlation between the calcium-magnesium ratio and crop yields. He believed that the sig-

nificant factor determining yields was the amount of active calcium in the soil. The addition of lime to the soil is beneficial—not because it changes the calcium-magnesium ratio, but because it increases the replaceable calcium in the soil. Some of the calcium taken up by the plant is probably used for the neutralization and precipitation of the acids in the plant sap.

Calcium, as calcium pectate, is definitely known to be one of the components of the middle lamella of the cell wall and is considered by some scientists to enter into the composition of protoplasm and certain types of proteins in the cell. Tests indicate that calcium plays a significant role in increasing the percentage of seed germination (8). Its effects appear to be related to its nutritional value and cannot be ascribed to changes in soil reaction.

If soil or a culture is deficient in calcium, symptoms appear in plants in the form of the inrolling of the leaf margins, and the leaves later become dry and twist around the stem. At a later stage, terminal growth stops, and the leaves become necrotic. A deficiency of calcium is also believed to cause a disturbance in the translocation of carbohydrates and proteins and to be injurious to the growing rootlets of plants (27).

B. *Calcium in the Animal*

In the animal, calcium is the outstanding single constituent of bones and teeth, which together contain all but a small fraction of this element in the body. However, this small fraction circulating in the blood and permeating the soft tissues is tremendously important in determining the state of health (277). The normal rhythm of the heart muscle and the excitability of the other muscles and nerves depend on their being constantly bathed with blood or lymph containing the physiologically normal amount of calcium. The clotting of the blood and the regulation of the permeability of the membrane also depend on a constant maintenance of this element (323).

Calcium occurs in bones in the ratio of three moles of tricalcium phosphate to one mole of calcium carbonate, and this proportion persists regardless of whether calcium is being deposited or withdrawn from the bone. The normal daily intake of calcium is approximately one gram. Although this amount may be taken into the

Courtesy Missouri Agricultural Experiment Station

Paralyzed hind legs, enlarged knee joints, soft bones, and other symptoms of rickets occur when an animal consumes only feed grown on calcium-deficient soil. These symptoms are present in this animal, which, because of lack of calcium, "went down" and is unable to rise.

body, it is by no means sure to be assimilated and used, as frequently a large proportion in the diet is in an insoluble form, so that assimilation is impossible.

The ratio of calcium intake to phosphorus intake in the body should be approximately one to two, since at this ratio the vitamin D requirements are at a minimum (268). An upset of the calcium-phosphorus-vitamin D balance eventually results in one of the several forms of rickets. A deficiency of phosphorus with calcium normal leads to overgrowth of the osteoid tissue at the ends of long bones and rib junctures. Because of retarded calcification, the bones fail to acquire normal rigidity, and, as a result of pressure of the weight of the body, the ends tend to enlarge. When calcium is low and phosphorus is normal, tetany results (280), bone growth stops, and resorption of tissue will occur, so that the need for calcium and phosphorus may be reduced. By forming insoluble compounds with calcium, excessive phosphorus in the diet will reduce the amount of cal-

cium which it is possible to absorb. When both calcium and phosphorus are reduced, bone growth also ceases and osteomalacia results.

Adequate amounts of vitamin D are necessary for the proper utilization of calcium and phosphorus; and if this vitamin is not formed in a sufficiently large amount, rickets will occur even in the presence of sufficient calcium and phosphorus. On the other hand, sufficient vitamin D will not make up for a lack of these two vital elements. Too much vitamin D taken constantly tends to reduce the calcium and phosphorus content of the body by increasing the amount excreted, a condition that should be taken into consideration by vitamin-pill addicts. Among the gross symptoms of overdosage with irradiated ergosterol (vitamin D) are rapid loss of weight and anorexia.

Calcium and phosphorus are readily moved in and out of bones according to the immediate needs of the body, and temporary deficiencies may frequently occur with little harm because of the considerable buffer action of the body.

c. *Calcium Deficiency in the Soil*

Calcium deficiency in the soil has come to be plant-nutrient problem number one in agricultural production (9), and calcium is now considered to be far more important in the production of food high in nutritive value than was formerly believed. Calcium, although known to be necessary to plant and animal nutrition, has not been regarded primarily as a fertilizer but rather as a means of decreasing the acidity of the soil prior to the seeding of a leguminous crop. This belief has persisted even though it has been found that lime added to highly buffered heavy soils was beneficial to the crop where no change in acidity could be shown (6).

The present concept of the value of calcium includes its importance in mobilizing nitrogen and phosphorus or, in other words, in producing proteinaceous rather than carbonaceous vegetation (235, 308). With calcium mobilizing both nitrogen (4) and phosphorus (12, 13), and with all three of these nutrients associated with protein, which is the basis of growth, calcium is apparently more significant in growth promotion than direct measurement of calcium content of crops would make it appear.

In determining the composition of the plant, calcium, phosphorus, and potassium may function as variables, according to Albrecht (7). However, phosphorus may be considered almost a constant in nature, since it is low in quantity and low in chemical mobility compared with the other two elements. Taking this into consideration, the calcium-potassium relation becomes a controlling factor in determining the protein ratio of the plant and, hence, in the plant's nutritive value to the animal.

There is a calcium-deficient area in the sandy and acid clay soils stretching east from Texas along the Gulf states to Florida and north along the Atlantic Coast to Maine. The deficiency may be measured by comparative analyses of the calcium content of surface and spring waters in this area and similar waters in other parts of the country (84).

Isolated pasture lands in southeastern Ohio are deficient in available calcium, and the forage produced there is also low in calcium (28). Within the same counties and drainage basin are pastures not deficient in calcium; so here, as in many other parts of the United States, calcium deficiency may be a local problem, depending on several factors, including erosion, fertilizer practice, and the degree to which the land has been cropped. With improper farm practices, lime, because of its solubility, is one of the first elements to be leached out (111). Dove (84) found that not only were the soils of Maine deficient in calcium, magnesium, and iron, as evidenced by a water analysis, but that a considerable part of the available calcium in the native vegetation was not utilized by animals because of the low antirachitic value of sunlight at that latitude. He considers significant the fact that Maine was fifth among the forty-eight states in the percentage of physical rejections for the armed forces.

Although calcium deficiency in animals is not so widespread as phosphorus deficiency, if we are to judge by published reports, it is nevertheless not confined to any one part of the country. The largest area of general deficiency appears to be on the acid, sandy soils of Florida and Louisiana, although complete soil studies have not been made (37).

Calcium deficiency has been reported in animals in Nebraska, Virginia, and West Virginia (136). Becker and associates (34) re-

Courtesy Missouri Agricultural Experiment Station

This cow's backbone became a solid instead of a jointed one because her life on calcium-deficient soil sacrificed her backbone in calf-rearing. She rebuilt it as a solid section when it was too sore to be flexible. Note the lower part as a solid, instead of four separate vertebrae. Poor top lines suggest poor nutrition that stems from the soil fertility.

ported that grass forages grown on the Florida soil contain relatively small amounts of calcium. Dairy cows dependent on home-grown roughage withdrew mineral matter from their bones to the extent that they were easily broken. Both production and health were severely affected. These troubles were due to a lack of calcium rather than phosphorus, as was indicated by the fact that the phosphorus intake was greatly in excess of requirements through the concentrates being fed.

In dairy feeding, where high phosphorus concentrates are included, the low calcium content becomes the main factor in the troubles noted. Legume pasture or hay always contains enough calcium to meet the animal's needs, and thus variations here are of minor importance. In many soils, however, the calcium supply, the acidity, or other factors are such that legumes will not grow normal-

ly or even at all. Grasses are much less affected by these factors but are always lower in calcium than legumes, and the satisfactory growth they frequently make is no proof of an adequate calcium content. Thus generalizations regarding the adequacy of grass hay in calcium content for animal nutrition are unsafe because of the very great variations that can occur.

In Wisconsin and Pennsylvania, the fact that "poor rations" based on timothy hay grown on acid soils were found entirely adequate for high milk production, without mineral losses from the bones over several lactations, resulted in the conclusion that a ration with timothy hay as roughage may provide satisfactory nutrition (206). The hay used ranged from 0.35 to 0.50 per cent calcium. In New York, on the other hand, fifty samples of timothy hay from good and poor soils ranged from 0.14 to 0.35 per cent calcium (206), and it is understandable that some of the timothy hay grown

Courtesy Missouri Agricultural Experiment Station

A "sick" sheep, because his hay was grown on soil needing lime and phosphate. Hay grown on soil treated for deficiency gave healthy sheep. It also had them ready for breeding use on schedule, whereas these "sick" sheep were "late" breeders.

in New York may not provide satisfactory nutrition for dairy cows even though some of that from Wisconsin and Pennsylvania does.

In general, the calcium content of plants is lowest on acid soils, and calcium and phosphorus content may vary inversely under the influence of moisture and certain fertilizer applications. This fact is especially interesting because of the intimate association of these elements in animal metabolism and the importance of having them present in a certain ratio to each other. In areas of phosphorus deficiency, the calcium content of the forage is generally high. Such is the case in Minnesota (90), where the calcium-phosphorus ratio is sometimes as high as ten to one. This may be a contributing factor, along with inadequate phosphorus, in animal troubles.

The possibility of calcium deficiency among farm animals depends on the calcium content of the forage, the amount of roughage consumed, the ratio of calcium to potassium, the amount of vitamin D in the feed, the environment, and the product—milk, meat, or wool.

Calcium and phosphorus deficiencies may make their appearance early in the life of the animal. In some localities, animals born in early winter develop rickets in late winter or early spring. Their bones break readily and the pelvic-spine joints separate. The animal "goes down" when the farmer believed it was "doing well" (10).

Disturbed reproduction processes are another consequence of calcium and phosphorus deficiency. On some less fertile soils, cows are inclined to breed only every other year. The backbone of such a cow may reveal that she sacrificed part of this organ for fetus production and used the succeeding year to replace it rather than to indulge in another reproductive cycle. Males may lose their breeding capacity on deficient forage feeds grown on deficient soils. In an experiment carried out at the University of Missouri (10), male rabbits fed forage grown on calcium-deficient soils became impotent. Their litter mates on feeds grown on calcium-rich soils were not impotent. When the feeds of these lots were interchanged, the situation was reversed.

In another experiment at the same institution, it was demonstrated that liming the land made lespedeza hay a much more efficient growth producer and also increased the hay yield by about 25 per cent. Each pound of limed hay, moreover, was about 50 per

cent more efficient in feeding value to the animal that ate it. Unlimed hay was deficient in some quality which would help the animal build the calcium and phosphorus into its own body. Introduction of calcium into the digestive tract, and from there into the animal's body, was apparently not enough. These essential minerals must first be absorbed and stored by the plant before they can be of maximum value to the animal.

Albrecht has summarized this situation in the following manner: "As the soils become poorer for certain crops and as substitutes are used, the substitute crops tend to become mere mineral haulers. Unfortunately, the minerals they deliver consist more of silica with no food value, in place of calcium, phosphorus, and all else of nutritive value that comes with them. An unbalanced plant diet offered by the soil cannot be offset by minerals added to the vegetative bulk used as feed any more than wheat straw would be good feed when supplemented by saltpeter, limestone, and bone meal. Synthetic diets, at best, leave much to be desired." Gunderson (119), although not opposing Albrecht's point of view and agreeing with him about the general paucity of calcium in the diets of men and animals in many places, is not so critical of the use of inorganic forms of calcium in the diet. He suggests that families on extremely low budgets would benefit from the addition of calcium salts to certain foods which they consume regularly.

One field of research in which a great deal of work needs to be done is that of determining the relative values of inorganic forms of minerals in the animal diet and the organic forms, or, in other words, those which are consumed as plant or animal products. Calcium would be one of the most important subjects of this research.

Recent observations or reviews on calcium deficiency in animals have been made by Corlette (67) and Fairbanks (98), and on the calcium needs of plants by Albrecht (9).

VI. MAGNESIUM

Magnesium is essential to both plants and animals but is usually present in the plant in smaller amounts than calcium. It is relatively more abundant in the parts of plants concerned with vital processes,

Courtesy Horticulture Department, Ohio State University and Ohio Agricultural Experiment Station

Magnesium deficiency in *Chrysanthemum*

The plant on the right is magnesium deficient; the one on the left, normal. Deficient plants develop a chlorosis that is characterized by the loss of chlorophyll between the veins of the leaves. Lower leaves are the first to be affected.

such as seeds and foliage, than in storage parts such as stems and roots.

Boehm (42) studied the specific effects of calcium and magnesium on plants and discovered, in 1875, the toxic effects of magnesium salts on plants growing in solution cultures. However, it was not until some few years later that the remedial power of calcium for magnesium was demonstrated and the ratio of the two elements for the best growth of plants suggested.

The prolonged investigations of Oscar Loew on magnesium and its functions in plant nutrition produced some important results. In discussing the role of magnesium in the plant, he concluded (177) that one of its functions was to serve as a carrier for phosphoric acid, since magnesium, like phosphorus, accumulates in the seed. Considering the rapidity with which magnesium salts are dissociated, Loew believed that they would present the phosphoric-acid radical in a form favorable for assimilation. The result of numerous analyses can be cited to show that magnesium is usually abundant in the plant where nucleo-proteins are being formed. If magnesium has such a function, it is evident that a small quantity could be used repeatedly as a carrier of phosphoric acid. The calcium-magnesium ratio of Loew and its refutations by Lipman have already been discussed.

The only metal contained in chlorophyll is magnesium (322); and when this element is deficient, chlorosis results (31). Plants differ markedly in their response to a deficiency of magnesium in the soil. For example, buckwheat and spinach are very sensitive, but grasses, clover, and potatoes are only slightly affected. the light, sandy soils in humid regions are more subject to magnesium depletion than heavier soils in drier regions. In these light soils the relatively low magnesium content, which is easily leached, has resulted in the appearance of magnesium deficiency in a number of crops. Garner and associates in 1923 (114) showed that "sand drown," a common chlorosis of tobacco along the Atlantic coastal plain, was caused by a magnesium deficiency and that it could be cured by applications of some salt of the element. Magnesium deficiency has been reported in the crops of Maryland, Virginia, North and South Carolina, and Illinois (84). Aroostook potatoes respond to magnesium because the soils of that region of Maine contain very little of it (65).

After Wheeler and Hartwell (318) had shown that application of magnesium salts to certain Rhode Island soils was beneficial to several crops and that one application of dolomitic limestone would supply the magnesium requirements for a number of years, the application of this form of the mineral became one of the standard soil treatments. With a soil low in magnesium, however, the application of calcitic lime aggravates the magnesium deficiency.

Dolomite is satisfactory for many crops with a long growing season, particularly those making optimum growth at relatively high soil pH levels. The quantity added is determined by the pH value of the soil, but a ton-per-acre application broadcast will usually supply the magnesium requirements for a number of years and will be satisfactory for most crops. If, however, water-soluble magnesium salts are used, it may be desirable to make annual or frequent applications because of losses from the soil through leaching.

In the animal, magnesium is essential in the composition of bone and teeth and plays an important part in the metabolism of phosphorus and the starches and sugars. It is essential to life; for if an animal is deprived of the element, it becomes increasingly irritable, its heart action is not controlled, there is kidney damage, and—if the experiment is carried to extremes—the animal dies in convulsions (167). Knowledge of the importance of magnesium in animal nutrition has lagged far behind that of the other inorganic elements, with the exception of those present in extremely minute quantities. The amount of magnesium taken in varies with the type of food. The chief source in the average diet is green vegetables, and the problem of specific magnesium deficiency in the human diet does not arise normally.

There appear to be no reports dealing with magnesium deficiency in cattle under natural conditions, but in most cases this condition would probably be associated with or might be mistaken for a deficiency of calcium.

There have been several reviews on the value of magnesium in plant nutrition (96, 156, 204, 329) and in animal nutrition (85, 86, 99) in the past few years, in addition to the general reviews already mentioned. Lawless, in 1941 (168), reviewed the literature on the effect of magnesium on citrus.

The need for additional research on magnesium is not so pressing

Courtesy the American Potash Institute, Inc.

An alfalfa plant exhibiting symptoms of potassium starvation. Chlorosis appears first as small dots, then it involves the entire leaf margin and is followed by death of the tissues which turn brown. The edges of the leaves become broken and ragged in the more advanced stages.

as on some of the other elements, but the best ratio of magnesium to several of the other essential elements has not been conclusively demonstrated, especially with different types of soils as a variable.

VII. POTASSIUM

POTASSIUM, another of what are sometimes known as the macronutrients, is very widely distributed over the earth as a common constituent of many silicate minerals. The amount found in most soils is high compared with that of nitrogen and phosphorus. However, there are some cultivated soils—such as sands, sandy loams, mucks, and peats—which may be low in both total and available potassium. In general, good soils average 2 per cent of potash in contrast to about 0.24 per cent nitrogen and somewhat less phosphorus (66). In spite of this large reserve, potash is usually not available in great amounts, as most of it is present in relatively insoluble compounds.

Root and tuber crops and crops producing starch or sugar, such as potatoes and sugar beets, remove a large amount of potassium from the soil each year (7). This may amount to as much as 125 pounds per acre in the case of common beets (66).

On some soils the potash supply has remained at a productive level for years. In many instances, however, where crop after crop has been produced on the same soil and sold away from the farm in one form or another, the nutrients, including potash, have gradually but surely been depleted.

Potassium is absolutely essential for plants and cannot be entirely replaced by any other element, but its exact role in plant physiology is not known. It is only by noting the effects on the plant of its absence that its exact function is deduced. Without sufficient available potassium in the soil, plants become reduced in vigor, are more susceptible to disease, and fail to develop normally.

In cereal grains, sufficient available potassium insures plump kernels and gives stiffness to the straw. It may act as a nitrogen buffer by slowing down the effects of excessive nitrogen, and also may prevent the rapid maturity which may be induced by too much available phosphorus.

Nobbe and his associates (227) seem to have been the first to point out the necessity of potassium for the formation of carbohy-

Courtesy the American Potash Institute, Inc.

Potash and nitrogen deficiency in corn

The leaf at the left is normal; the leaf in the middle is deficient in nitrogen. The yellowing begins at the tip and progresses along the midrib. The leaf at the right is deficient in potassium. The brownish edge scorch is characteristic of potash deficiency in corn.

drates in plants, although the general essentiality of the element was observed a few years earlier. The present opinion seems to be that a high potassium content of the soil when not balanced by other essential elements, especially calcium, tends to produce a plant especially high in carbohydrates. A normal amount when calcium and phosphorus are deficient will have the same effect and will produce plants of a very low biological value (282) with a lesser change in caloric value. On the other hand, a more nutritious proteinaceous and less carbonaceous plant grows when the potassium-calcium ratio is weighted in favor of the latter element, a fact that should be taken into consideration in planning crop rotations. When an actual potassium deficiency occurs, carbohydrate synthesis is diminished, although all investigators are not in complete agreement on this point.

Forest soils are generally richer than prairie soils in potassium, but usually contain less phosphorus and calcium (59).

More potassium than sodium is present in the animal body, mostly in the muscle tissue. Nevertheless, the daily sodium requirements are at least twice the potassium requirements (323), and the concentration of sodium in the blood plasma is eighteen times that of potassium. The intake of large amounts of potassium does not increase this concentration.

Potassium deficiency in animals does not occur under natural conditions; but in the laboratory young rats fed on diets supposedly adequate in all respects, but containing only traces of potassium, grew at a very slow rate. Their length of life did not seem to be affected (208), but their fur was thin and rough and sexual maturity was delayed. The potassium in the muscles, heart, and kidneys was lowered, and the sodium increased; and all of the potassium-deficient animals showed cardiac and renal hypertrophy.

It is apparent that the animal body makes some use of potassium. However, the requirements for normal growth are amply supplied by the potassium content of a diet adequate in other respects, and most diets contain several times the amount necessary to meet the body's need. Therefore, it cannot be considered that potassium is one of the more essential elements in animal nutrition.

A discussion of potassium with special emphasis on its functions in relation to human physiology is found in a publication by Shohl (280).

VIII. SULFUR

From the time of Liebig, it has been known that sulfates are necessary for plant growth, and sulfur fertilizers have been used extensively both in this country and in Europe. The amount needed by the plant. however, was underestimated (214) until recently, and it has been only in the past few years that any thought has been given to the application of sulfur as a fertilizer.

According to Alway (18), the history of sulfur fertilizers may be divided into three periods: first, the period of gypsum; second, the period of superphosphate; and, third, the modern period. In the first, covering almost a century up to 1845, gypsum was commonly used, and its effects frequently overestimated. In the second, extending from 1845 to the early part of the present century, the need for sulfur additions to the soil was ignored and the use of gypsum discouraged. What we may consider the modern period started when the assumption that the natural supply of sulfur is everywhere sufficient for crops was questioned and practical tests were made.

It is impossible to trace the first use of gypsum as a fertilizer; but, possibly as the result of several experiments carried out in the years around 1769 (18), the use of gypsum spread in an extraordinary manner, and its application to agricultural land became general in western Europe and many parts of the United States. The promoters of gypsum fertilization greatly exaggerated its value and importance, speaking of it as a universal manure, applicable to every variety of soil, for every variety of crop. A reaction to this enthusiasm soon set in, however, and gypsum was eventually found to produce its best effects on a small group of plants such as clover and lucern, and only on certain soils. This period was brought to a close with the beginning of accurate experimental work with fertilizers; and investigators concluded that, although the sulfur content of the gypsum was valuable, the striking results obtained in some cases were due rather to the calcium content.

A lack of interest in gypsum and its mode of action was evident during the following half-century when agricultural research was developing rapidly. The manufacture of superphosphate had begun,

which, while providing phosphorus in readily available form, at the same time furnished even more sulfur that was equally available, In practice, whenever a fertilizer was needed, superphosphate was usually employed—either alone or in combination, frequently with ammonium, potassium, or even magnesium sulfates.

There was, therefore, a greatly increased but not planned use of sulfur in fertilizers before concentrated commercial phosphates appeared. Since crops that responded to gypsum did as well or better with superphosphate, gypsum was forgotten for the time being and the value of sulfur in plant nutrition was practically lost sight of.

The third or modern period in the evaluation of sulfur as a fertilizer arrived slowly, being brought into focus in 1911 by Hart and Peterson (130), who demonstrated the needs of crop plants for sulfur and pointed out to the agronomist the advisability of a change in attitude toward the nutritional value of sulfur to the plant.

The amount of sulfur removed by crops is about equal to that of phosphorus, but erosion and leaching take more sulfur than phosphorus out of the soil. In brassacaceous crops,[1] and onions and their relatives, the sulfur content of the plant greatly exceeds the phosphorus content (72). Sulfur, unlike phosphorus, is washed down in rain and snow, especially in urban areas, and, therefore, where the land is not cropped or pastured heavily, the amount thus acquired may be sufficient to make up for all losses of the element. Alway and associates (19) found that the sulfur deposited in one year by rain, snow, and dust in Minnesota varied from one hundred pounds per acre in Minneapolis to less than five pounds in a sulfur-deficient area in the northern part of the state. In general, however, fifteen to thirty pounds per annum are deposited in rural communities (97, 157).

Recognized sulfur deficiencies in crops occur infrequently and are usually associated with early stages of growth under dry conditions. Sulfur-deficient areas have been reported from Oregon, Washington, Idaho, California, and Minnesota, as well as from the Canadian provinces of Alberta, Saskatchewan, and Ontario (18).

Sulfur occurs in plant tissues chiefly in proteins, volatile compounds, and sulfates. In the proteins, it exists for the most part in the form of cystine. In the volatile form, it occurs in mustard oil,

[1] The cabbage and closely related species of the mustard family.

Courtesy Horticulture Department, Ohio State University and Ohio Agricultural Experiment Station

Sulfur deficiency in *Chrysanthemum*

The plant on the right is deficient in sulfur; that on the left, normal. The effects of sulfur deficiency in plants are characterized by loss of green color in the younger leaves of the plant, including the veins. When the deficiency is severe, all of the leaves may be light green in color, but the lower leaves do not dry up as they do in the case of nitrogen deficiency.

allyl sulfide, vinyl sulfide, and the mercaptans. These volatile compounds are most abundant in the *Cruciferae*,[2] but some are to be found in the onion tribe of the *Liliaceae*,[3] in the *Tropaeolaceae*,[4] and in other families. The mustard oils do not occur as such in the plant but are found in the form of glucosides.

Sulfur functions in the formation of protein and other plant constituents, and it has been noted that plants with a high protein content or especially rich in organic sulfur compounds.respond most markedly to the application of sulfur as a fertilizer. Alfalfa grown on soils treated with sulfur was found to contain a higher percentage of protein than alfalfa grown on soils not so treated (229); and red clover with a deficiency of sulfur had a limited synthesis of protein (304), resulting in a restricted growth.

Aside from functioning as a building material, sulfur produces certain formative effects in plants manifested by an increased root system (157, 215, 244), an effect on the chlorophyll, and an effect on the nodules of legumes. Plants deficient in sulfur have a pale-green color, which changes to a dark, healthy green when this element is applied as fertilizer (88). Just what the physiological effect of sulfur is on the chlorophyll is not known, but it appears to be indirect since chlorophyll does not contain sulfur.

Legumes growing on a soil containing sufficient sulfur will show a larger number of nodules per plant than legumes growing on a soil more or less deficient in the element. Powers (247) attributed this stimulating effect to the action of sulfates on the legume bacteria. It has been generally noted that plants deficient in sulfur have the same general appearance as those which have been completely deprived of nitrogen.

As sulfur is a constituent of protein, it is present quite generally in animal as well as vegetable matter. However, it is not ordinarily considered in connection with problems of mineral deficiency in animals, because if the diet contains sufficient protein of the right kind, this element will be furnished in adequate amounts. If the animal or human diet should be deficient in sulfur, that element would be directly connected with the more inclusive problem of protein deficiency.

[2] Mustard family.
[3] Lily family.
[4] Nasturtium family.

Green plants, because of their synthetic power, are the ultimate source of sulfur for animals which are unable to form proteins from the inorganic sulfates (323). The amino-acid cystine has long been known as a sulfur protein constituent, and more recently methionine has been discovered. Both are indispensable and represent the most important sources of sulfur in metabolism. Although proteins are the main sulfur source, other organic sulfur compounds from plants are important in animal economy. Vitamin B_1, or thiamin, is one of the biologically important sulfur-containing compounds, and cystine has been isolated as the sulfur constituent of insulin.

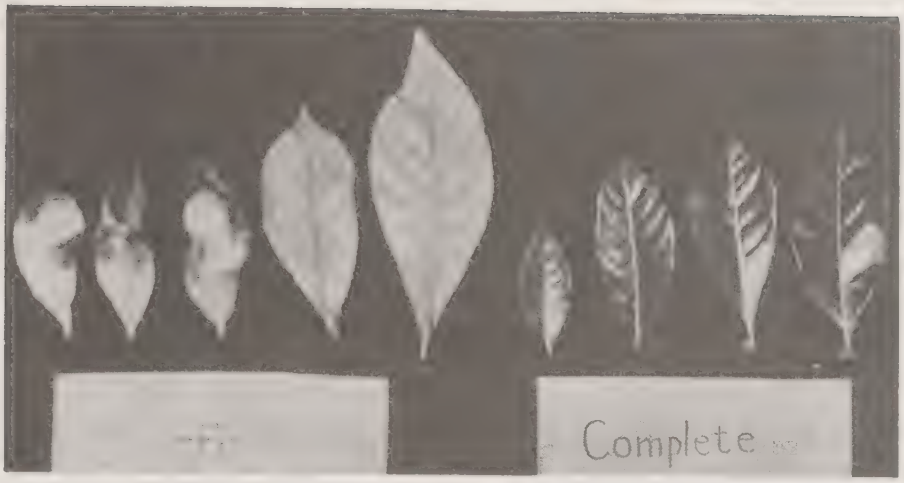
Many conflicting opinions exist concerning the use of sulfur in the treatment of various pathological conditions. There is no evidence that colloidal sulfur or inorganic sulfur introduced into the body in any way can be used for the synthesis of the sulfur-containing amino acids, which alone can be utilized by man as a source of this element (76). Several reviews of the use of sulfur in plant and animal nutrition have recently been published (18, 73, 76, 108, 134, 174, 229).

IX. IRON

Iron has long been recognized as essential to normal plant development and is directly connected with the functioning of the chlorophyll, although not actually a part of the molecule. If plants are deprived of iron, actually or physiologically, the leaves turn yellow, starting with the young growth.

The quantity of iron needed by a plant at any one time is very small, but plants vary widely in the amount which they contain (298). Of the plants used in experiments, apples and melons contained the least iron, and cowpeas, dandelions, parsley, water cress, and spinach contained the most. Formerly a trace of iron in soluble form was all that was considered necessary in the nutrition of plants, and little attention was paid to the form in which it was presented. Now, however, it is known that not only the quantity but also the form has considerable effect upon plant growth and development (199).

Although there is an abundance of iron in almost all soils, the exchangeable iron in calcareous and other soils with a pH around



Courtesy Horticulture Department, Ohio State University and Ohio Agricultural Experiment Station

Iron-deficiency symptoms in *Gardenia*

The leaves on the left are from the upper portion of a plant receiving insufficient iron. Those on the right are from a healthy plant. Iron deficiency will occur in *Gardenia* when a high pH makes the iron present in the soil unavailable to the plant.

the neutral point may be so low that the plants are unable to absorb enough for healthy growth. Iron may be present in the soil in three forms: undecomposed silicates, colloidal clay, and hydrated or anhydrous oxides. The reaction of the soil and the prevalence of oxidizing and reducing conditions largely govern the solubility of iron, which, in general, is quite soluble in the more acid soils. The addition of any reducing organic matter, such as crop residues and manure, increases the available supply by temporarily reducing the iron to a soluble form. The complex ions formed with the organic matter hold the iron, even after oxidation, in solution at pH concentrations that would otherwise precipitate ferric hydroxide.

Some plants are chlorotic and do not make a normal growth on certain calcareous and manganese soils. The most effective way found to correct this condition is spraying the plants with iron solutions. It has been observed that when plants which have been receiving sufficient iron are suddenly deprived of it, the new growth is nearly white; or when chlorotic plants are sprayed with iron compounds, the parts not actually touched remain chlorotic. This indi-

Courtesy Horticulture Department, Ohio State University and Ohio Agricultural Experiment Station

Iron deficiency in *Chrysanthemum*

The plant on the left is deficient in iron; that on the right, normal. Note that the yellow color is more pronounced on the young growth, a characteristic of iron deficiency.

cates that iron is immobile in plants and is not readily withdrawn to newer organs.

Soluble iron compounds are not compatible with soluble phosphates in fertilizer mixtures since they form insoluble compounds that are largely unavailable to plants. Thus soils having considerable iron in an unavailable form should be treated with acid-forming fertilizers such as ammonium sulfate or elemental sulfur to increase the acidity, or liberal amounts of organic matter should be added to increase the availability.

Although the amount of iron in an animal is small, it is vitally important to the living processes concerned with the transportation of oxygen and the metabolism of food materials within the cells. About two-thirds of the iron in the body is in the hemoglobin of the red blood cells, but the element is also present in the liver, spleen, and bone marrow, and to some extent in the muscle tissue.

Anemia results when the iron intake is low or when the iron is not properly assimilated by the body so that it does not reach the bone marrow, but some nutritional anemias may arise from other causes. In anemia that is benefited by iron treatment, the red cells are smaller and contain less than the normal amount of hemoglobin per cell. This type of anemia sometimes occurs among infants on a milk diet, and the observation has been checked in the laboratory by feeding rats on an exclusive diet of whole milk until anemia developed (121). This anemia can be prevented by the addition of inorganic iron, because whole milk contains a relatively low amount of the element.

If there is no actual loss of blood, iron deficiency is most likely to occur during the first two years of life and at puberty, and, in women, during pregnancy or toward the end of the reproductive period of life. However, many children develop an iron deficiency at other times between birth and adolescence. During the first four to eight months, the child receives very little iron since milk contains only a slight amount of this element. It is essential, therefore, that the diet of the pregnant woman contain a rich supply of iron, especially during the last three months before parturition; otherwise anemia is likely to develop in the child. According to Forman (106), the response of the anemic child to adequate iron therapy makes this one of the most satisfactory procedures in medicine. The child's appetite increases and his heart rate, frequently high while anemia persists, returns to normal. He shows an improvement in gastrointestinal function, in sleep patterns, and in disposition generally. Symptoms of fatigue and malaise disappear, and physical activity increases.

Although copper and cobalt do not seem to be essential to the absorption or storage of iron, there is a definite connection between the three elements in relation to nutritional anemia. Some persistent forms of the disease which refuse to clear up with the usual iron therapy respond when copper or cobalt or both are included in the treatment. The specific physiological functions of copper and cobalt will be discussed in the chapters relating to these elements.

Iron deficiency, often reflected in livestock anemia, is sometimes caused by an actual lack of iron (300) and sometimes by the high pH of the soil which makes the iron unavailable (24).

In New Zealand, "bush sickness" of sheep was found to be caused by a lack of iron. In this case, since the amounts of calcium and manganese capable of lowering the available iron by antagonism were themselves not present in any appreciable amounts, the lack of iron was believed to be due to leaching from the soil.

There are large areas in Florida where a disease known as "salt sick," characterized by anemia, has been known for over forty years (77). The recovery of animals and the restoration of hemoglobin took place after the administration of ferrous ammonium citrate which contained a trace of copper (33). Here the iron-deficiency explanation was supported by an analysis of the forage grown on the "sick" soils (226). Surface soil in healthy areas was found to contain approximately ten times as much iron, twice as much copper, and five times as much phosphorus and calcium as that in the salt-sick areas (55). Iron deficiency in soil has also been reported from Oregon, Colorado, Kansas, Alabama, Arizona, and Massachusetts (37).

The best-known example of a general nutritional anemia of human beings caused by a lack of iron was found among the children from certain rural areas in Florida, and has been reported by Abbott and her associates in a series of papers from the Florida Agricultural Experiment Station (1, 2, 3). The iron content of turnip greens from the deficient soils supporting anemic children was 56 parts per million in contrast to 258 parts per million in turnip greens on normal soils.

Two reviews on iron in human and animal nutrition have recently been published (41, 138).

X. COPPER

Although the value of copper as a fungicide has been known for many years, the possibility that copper might be essential in plant nutrition was apparently not considered until comparatively recently (289), when solution culture work was done to prove its essentiality. Through a refined means of nutrient salt purification, by which practically all of the copper present as an impurity was eliminated, and by redistillation of the necessary water through pyrex or quartz, deficiency symptoms were obtained in several species of

Courtesy Florida Agricultural Experiment Station

The "dieback" disease of citrus caused by copper deficiency

plants (290). One of the most characteristic symptoms noted in the laboratory is stunted growth accompanied by a more or less permanent wilting of the top of the plant. Chlorosis may or may not be present.

Two rather well-known plant diseases have been found to be caused by a deficiency of copper. The "dieback" disease of citrus, or exanthema, characterized by the death of the young growing tips

Tops of tomato plants grown in nutrient solutions—receiving no copper and 0.05 p.p.m. of copper

The plant at the left shows wilting of the upper part, with the upward inrolling of the margins of the leaflets characteristic of copper deficiency in the tomato. Symptoms were slight at first, the plant recovering on dark days and at night, but gradually the symptoms became more pronounced, and at the time this picture was taken the wilting had become permanent on the upper third of the plant.

The plant is in flower, but no fruit has yet formed. The older leaves show progressively less wilting, indicating that copper is not readily translocated within the plant.

The plant at the right, receiving 0.05 p.p.m. of copper, is normal, with turgid leaves and developing fruit.

Leaves from tomato plants grown in nutrient solutions—receiving no copper and 0.05 p.p.m. of copper

A. Leaf from tomato plant receiving no added copper.
B. Leaf from tomato plant receiving 0.05 p.p.m. of copper.
Each of these is the fifth nodal leaf from the top, on its respective plant. Note the characteristic upward inrolling of the margin and the deeper color of the copper-deficient leaf.

and resetting of the axillary buds below the dead part, was first shown to be caused by lack of copper in 1932 (20), although much earlier than this the application of copper sulfate to the soil or spraying with bordeaux mixture was known to prevent or cure the disease (103). The "yellow tip" or "reclamation" disease, most common on the peat soils of Europe but also found in other parts of the world, has been corrected by copper (285). It was also found

that the addition of copper sulfate made it possible to grow onions and lettuce on unproductive peat soils (94, 101). The most striking results, however, were obtained on the saw-grass soils of Florida, where almost useless land was made to produce good crops by fertilizing with copper sulfate (17).

Copper deficiency occurs particularly in peat, in soils with a very high humus content, and in very sandy soils with a low humus content. In the first two cases the copper present is apparently tied up by organic matter, for large amounts of copper sulfate may be added without harm; whereas in the sandy soils there appears to be an actual lack of copper, since a response is obtained by the application of small amounts of the salt and the lower limits of toxicity are soon reached. Experiments with copper treatment of tobacco soils in some of the southern states have shown that this crop responds markedly to additions of the element, even though no deficiency symptoms appear on any of the plants in untreated fields (115a).

Although the function of copper in plant metabolism is not known, the most frequently suggested uses are in the formation of chlorophyll and in the production of oxidative enzymes.

There have been several copper-deficiency diseases of livestock associated with deficient soils and forage. More than a decade before the role of copper in hemoglobin formation was discovered, investigators in northern Europe were studying possible mineral deficiencies in the forage in areas where a wasting disease of cattle called "*Lechsucht*" was common. In 1933 (281) its cause was established as a copper deficiency by the finding of marked differences in the copper content of the forage in healthy and sick areas and by the curing of the trouble with copper therapy. It has also been established that a disease of lambs reported from England, Sweden, Australia, and elsewhere, referred to as "enzoötic ataxia" or "sway-back" and characterized by nervous symptoms, is caused by a deficiency of copper in the ration of pregnant ewes. The "falling disease" and "stringy," or "steely," wool are also attributed to copper deficiency. The "falling disease," not uncommon in Australia, is characterized by staggering and falling, and results after a time in sudden death. It is associated with a very low copper content of the pastures, the forage of affected pastures containing as little as 1 part per million of copper on a dry basis as compared with 5 to 15 parts

Effects of addition of copper to tobacco fertilizers

The fifty sticks of tobacco on the right are from copper-treated soil, the fifty sticks on the left from untreated soil. Sampson County, N.C., 1945.

per million from the forage on healthful pastures. The disease may be controlled by adequate copper supplements (39).

"Stringy" wool seems to be the earliest and frequently the most obvious sign of copper deficiency, occurring even when the deficiency is not severe enough to cause manifestations of ataxia (38). A progressive change takes place from normal to straight, glistening, lustrous wool. The disorder is cured by supplying the sheep with copper, either as a drench or as a salt lick. Attempts to breed sheep with this type of wool result in ataxia in the offspring. These four and perhaps other copper-deficiency troubles (154) have certain symptoms in common and others that are individual. Further study of the specific pathology of each is necessary, and apparently copper has a more general effect than has thus far been demonstrated.

Although copper is not a constituent of hemoglobin, it is one of the most important factors in the utilization of iron for the formation of hemoglobin. The infant is born with a reserve supply of copper for use in the formation of red blood cells and hemoglobin; but these stores, enough for about the first year of its life, need later replenishment by the addition of copper-containing foods to the milk diet. Fresh cow's milk contains only about 0.2 to 0.8 parts per million of copper, but pasteurization will increase the copper content when the milk is passed over heated copper rollers, or when copper cooking utensils are used. The most striking effect results from making cheese in copper vats, when the copper content of the cheese may be as high as 18 parts per million. Fortunately, the best sources of copper are the iron-containing foods. In general, foods that will supply four to five milligrams of iron will also supply about one milligram of available copper.

Very little information is obtainable regarding woman's need for copper during the pregnancy and nursing periods. It is known, however, that the infant stores copper during uterine life and that the blood-copper level of the pregnant woman increases during the latter part of pregnancy. The increase in blood copper is associated with active blood formation in the mother and the infant's demands for copper. It is interesting to note that the blood-copper level is raised even in pregnant women who are anemic. Since young children, pregnant and nursing women, and women approaching menopause frequently become anemic, they should receive additional

amounts of iron, copper, and possibly cobalt in their diet. Supplementary anemia-preventing minerals may be consumed as pills or capsules; but many nutritionists consider this method advisable only as a remedy, not as a preventive. The mineral elements may be taken also in mineral-rich foods such as liver, shell fish, nuts, and molasses.

It is possible to increase the copper content of vegetables by growing them on land previously treated with copper salts, and it is not difficult to believe that mineral-fortified vegetables or other foods will be sold on the market at a premium over ordinary produce.

Little experimental work has been done in this field, and it appears to be one of the most promising for future research.

XI. COBALT

THE OCCURRENCE of deficiency diseases of sheep and cattle characterized by anemia is widespread throughout the world. In most cases, they can be associated with certain land areas, and a recognized cure has been to shift the animals from a "sick" pasture to one known to be healthy. Another early, and still useful, treatment was to add crude iron salts (limonite) to the feed. As this resulted in a cure, the diseases were for a long time ascribed to an iron deficiency. However, it was later found that if pure iron preparations were used, a favorable response was not always obtained; and when post-mortem examinations of the anemic animals revealed that the liver and spleen were filled with extra stores of iron, a deficiency of some other element was suspected. After some experimentation with copper, frequently a factor in anemia, and with other elements present as impurities in limonite, it was found that cobalt was the missing essential (26). With this in mind, investigators of livestock anemias evaluated their data and pursued with renewed interest the cases not responding to the usual treatments.

In Scotland, the "pining disease" was known as early as 1807, and is now believed to be due to a cobalt deficiency (68), although an investigation of the soils in areas where it was prevalent seemed to indicate that the iron content is low also. Other anemia diseases of sheep and cattle from various parts of the world responding to cobalt are: in Europe, "enzoötic marasmus," "coast disease," and "bush

Courtesy Florida Agricultural Experiment Station

A cobalt-deficient heifer

This animal has the characteristic rough-hair coat, gauntness, muscular in-co-ordination, and retarded growth caused by lack of cobalt in diet.

sickness"; in New Zealand and Australia, "Morton's Main disease" and "Denmark wasting disease" (137); in East Africa, "nakuritis"; in Michigan, "grand traverse" or "lakeshore disease"; in New Hampshire, "Burton-ail" (162); and in Florida, some phases of "salt sick." It cannot be said that these diseases are identical, for in few places are soil, climate, and other conditions the same. They have, however, several characteristics in common: The affected animals are retarded in growth, are anemic, and show progressive debility, so that in severe cases the animals are unable to rise and usually die. These diseases show a similar and amazing response to cobalt, whether given directly to the animal or applied to the deficient land.

In North America, in addition to Florida, New Hampshire, and the lake areas of Michigan and Wisconsin, cobalt deficiency in livestock has been reported from Canada and from the sandy coastal-plain area of Massachusetts (37). In New Hampshire, an interesting legend has been built up about a curse put on the region by the an-

cient Indian prophet Chocorua, which seemed real enough to the farmers who had difficulty in raising livestock there. Scientists, however, not standing in awe of the venerable warrior, found the troubles to be caused by a cobalt deficiency (162).

It is apparent that the requirements of cobalt per unit of body weight are lower for cattle than for sheep. Proof that the element is necessary for other species has not been produced. Horses thrive in the same areas where cattle and sheep develop serious trouble, and attempts to produce cobalt deficiency in rats have met with little success.

Considering the small amount of cobalt necessary, the problem of devising an experimental diet, adequate in other respects, which will not contain enough of the element to negate results is difficult, if not impossible, under present procedures of analysis. Until success in this direction is obtained, a complete knowledge of the specific role of cobalt can only be hoped for.

Neal and Ahmann (225) state that no cobalt was detected spectrographically in their basic ration for calves, but they also refer to the studies at the Florida experiment station which failed to find cobalt spectrographically in the forage from either "sick" or "healthy" areas. Thus usefulness of spectrographic methods for the determination of small amounts of cobalt is uncertain at present.

Soils containing less than 2 parts per million of cobalt commonly represent "sick" areas, while soils having amounts in excess of this figure are generally healthy. However, in Dartmoor, England, soils on which sheep suffer from "pining" have been recorded with a mean cobalt content of 3.9 parts per million compared to 16.7 parts per million on soils on which sheep recover (236). Sheep suffering markedly from cobalt deficiency have been found to recover completely with daily intakes as small 0.1 milligram. Even more surprising is the response to soil applications. Bonner and associates (43) have reported that an application of twenty-eight ounces of cobaltous sulfate per acre increased the cobalt content of the pasturage from an unhealthy level of 0.06 part per million to a healthy level of more than 0.1 part per million, which was maintained for at least a year. This rate of application, and even lesser ones, have been found to restore animals to health on "sick" areas, which is particularly interesting in view of the fact that there is no convinc-

ing evidence that cobalt is an essential element for the growth of higher plants.

In some "sick" areas, the livers of diseased sheep showed an extra amount of iron but a reduced copper content. Here both cobalt and copper were more effective than cobalt alone. In northern Michigan, cows with the "grand traverse" disease did well on cobalt alone.

The margin between deficiency and toxicity for cobalt is narrow. Larger doses of cobalt will produce a polycythemia in rats, mice, guinea pigs, rabbits, dogs, pigs, chickens, and frogs. This polycythemia represents a true increase in the number of red blood cells and apparently comes about through a direct stimulation of the bone marrow.

Cobalt is found in extremely small amounts in most of the organs of the human body, but the requirements for man are unknown. Favorable results have been reported from its use in treatment of anemia in infants. Cobalt has the ability to activate in vitro several of the enzymes, but it has never been identified as the physiologic ion in any enzyme system. It is apparently essential to normal red-blood-cell formation (74). It has a place in cell metabolism and possibly in those enzymatic processes which are in need of further investigation.

The distribution of cobalt and other elements in animal tissue has been reported (116) as determined with the aid of artificial radioactive isotopes, and the evidence has been confirmed that cobalt is found in its highest concentrations in the glandular organs.

A history of the investigations of variously named troubles in animals now recognized to be caused by cobalt deficiency in the soil and herbage has been summarized by Marston and associates (201, 202); likewise, several reviews including this subject and papers emphasizing cobalt in nutrition have recently been published (46, 54, 95, 100, 205, 206). Two other important papers include a summary of the occurrence of cobalt deficiency in the British Isles up to 1946 (237) and a history of cobalt deficiency in New Zealand (327). The last paper describes in detail the procedure used in locating the cause of a deficiency disease. Baudisch (30), in 1943, published a paper on the importance of trace elements in biological activity, which, while general in character, gives some data on the history of cobalt deficiency.

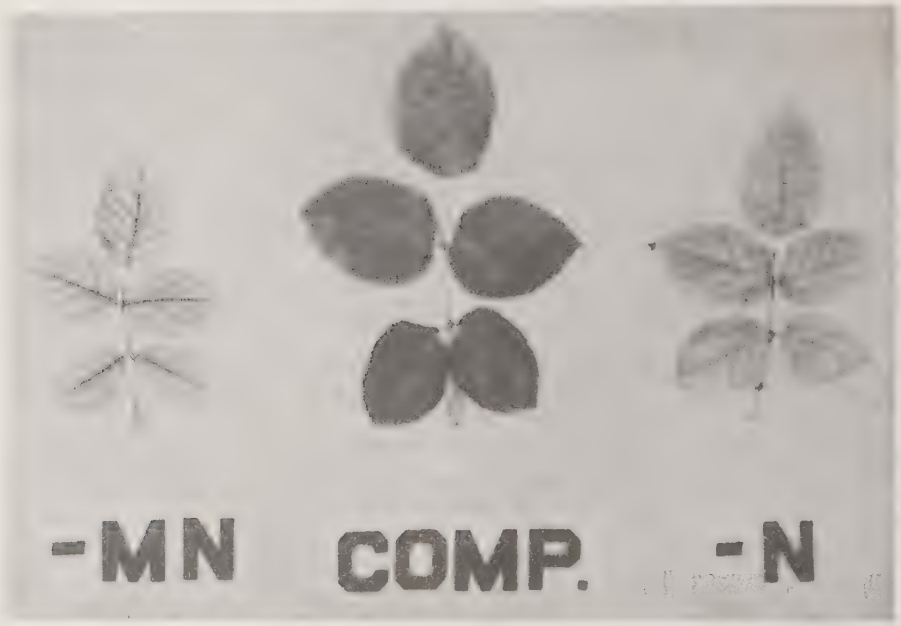
XII. MANGANESE

MANGANESE is present in all plants and animals and is an essential element in nutrition. It is widely distributed in soils and rocks but usually in small quantities. In 1774, Scheele (266), by means of an ash analysis, showed that manganese was assimilated by plants, but its essentiality to the plant was not definitely proved until 1922. At this time, McHargue (188), who had been experimenting with the element for some years, found that plants deprived of manganese made a stunted growth and produced no seed, while the check plants receiving manganese were normal. Prior to this, uncertain results were obtained because the iron salts used were almost invariably contaminated with manganese. McHargue found that crocks, supposed to be perfectly glazed, during the growing season absorbed from the soil with which they were filled enough manganese to supply the seeds of the succeeding crop grown in them. This occurred even when a manganese-free medium was used.

Courtesy New Jersey Agricultural Experiment Station

Manganese deficiency in cotton

The cotton leaves on the right are manganese deficient; the leaf on the left is normal.



Courtesy Horticulture Department, Ohio State University and Ohio Agricultural Experiment Station

Manganese and nitrogen deficiencies in the rose

The leaf on the left is from a manganese-deficient plant; that on the right, from one deficient in nitrogen; and that in the center, from a healthy plant. Chlorosis starts in the lower leaves of a nitrogen-deficient plant; but in a manganese-deficient plant, the upper leaves are the first to be chlorotic.

In addition to the stunted growth and failure to reproduce, the absence or scarcity of manganese in plants results in a disturbed carbohydrate metabolism, a decrease in the content of ash (214), and in many plants (including the tomato) a peculiar mottled type of chlorosis in which the areas between the small veins become yellow while the veins remain green.

Our understanding of the function performed by manganese in the metabolism of the plant rests almost entirely on theoretical grounds. There is some evidence that this element has a part in enzymic action and in nitrogen and carbon assimilation. Kelly (163) believed that manganese brought about a greater degree of mobilization of soil calcium and magnesium and caused a stimulation of oxidation in the plant and in the soil. The fact that a deficiency of manganese so often causes chlorosis indicates that the element is probably concerned also in the formation of chlorophyll.

Courtesy Department of Poultry Husbandry, Cornell University

Perosis or "slip tendon" in poultry caused by manganese deficiency

Courtesy Department of Animal Husbandry, Cornell University

Crooked front legs of rabbit caused by manganese deficiency

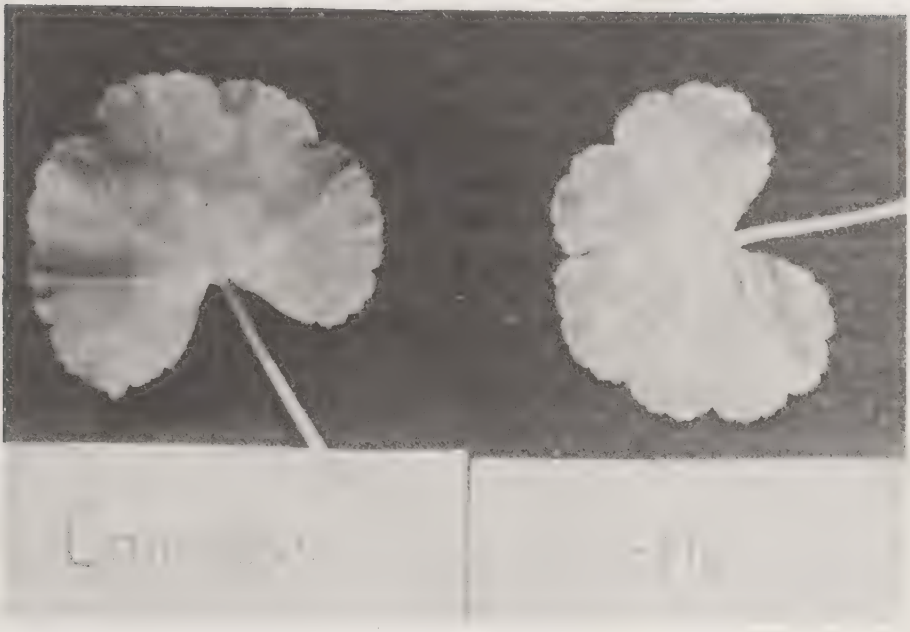
Extensive manganese-deficient areas exist in the United States (37), and the ability of a soil to supply available manganese is determined by the state of oxidation of the manganous-manganic system in the soil (276). The availability of manganese to plants is frequently complicated by the presence of other elements. For instance, manganese deficiency may be brought on by overliming a soil having a low content of active manganese, and the deficiency can be corrected by the application of manganous salts and acid-forming materials such as sulfur or by increasing the concentration of phosphates (13).

A definite iron-manganese ratio exists (286); that is, pathological symptoms produced with excessive iron seem to be identical with those produced when manganese is deficient, and vice versa. In other words, symptoms of iron toxicity correspond to those of manganese deficiency, and symptoms of manganese toxicity correspond to those of iron deficiency.

Several physiological diseases, the best known of which are "gray speck" of oats and "marsh spot" of pea, have been definitely proved to be due to a manganese deficiency, and it is possible to reproduce both of them in the laboratory.

It appears that manganese in very small quantities is necessary in the human diet, although its particular action in the body is not yet known. The greatest amounts have been found in the liver, pancreas, and suprarenal glands, and it has been suggested that the function of the element may be concerned with the development of the pituitary gland and the regulation of the sex glands. Experimental rats deprived of manganese show sterility in the males, and an interference with normal lactation and a lack of maternal instinct in the females.

A leg-bone deformity in chickens, known as perosis or "slip tendon," has been found to be caused by a low manganese diet or by a lack of the anti-perosis vitamin of the B complex, indicating some connection between the two, and this deformity may be reproduced under experimental conditions. The bones of chickens suffering from the disease have been found to contain only about one-third as much manganese as normal chicken bones, suggesting the possible necessity of this element in normal bone development.



Courtesy Horticulture Department, Ohio State University and Ohio Agricultural Experiment Station

Manganese deficiency in geranium leaves

The geranium leaf at the right is from a manganese-deficient plant; that on the left, from a normal plant. Manganese deficiency in many plants is characterized by a mottled chlorosis and in severe cases the tissue of the spots may become necrotic.

With a normal diet, there is little possibility of a manganese deficiency in the average human being.

A correlation of available manganese with ascorbic-acid production has also been found in plants (127). The ascorbic-acid content of tomatoes from plants grown on soils low in manganese is considerably less than of those from plants grown on soils with higher manganese content. In pot cultures, the application of 1 gram of manganous sulfate to 15,000 grams of Sassafras sandy-loam soil increased the ascorbic-acid content in tomato pulp from 142 milligrams to 243 milligrams per liter (139).

Several reviews on the value of manganese in plant and animal economy have appeared in the literature in the past few years (54, 81, 109, 153, 261, 275, 288).

XIII. ZINC

THE EARLIER agricultural chemists showed that the ash of some plants contained appreciable amounts of zinc. There were speculations on the significance of this unexpected element, but no one had a very clear idea of its physiological importance. Early negative reports on its value were without doubt due to the inability of the investigators to obtain nutrients free from traces of the element.

Studies of the effects of zinc on the growth of green plants began about 1913, when Voelcker (313) found that the addition of zinc up to 0.01 per cent had a stimulating effect, but above that concentration was toxic. Mazé (209), working with corn and using water cultures, determined in 1914 that zinc was necessary for plant growth, but his work received little attention. Irrefutable evidence of the necessity of zinc as a plant nutrient was published in 1926 by

Courtesy Florida Agricultural Experiment Station

Zinc deficiency in the orange

Acute zinc-deficiency symptoms on the orange (left), showing very small, smooth fruit and pointed leaves, with striking contrasts in leaf pattern; and (right) fruit and foliage from a similar tree one year after treatment, showing immediate resumption of normal growth.

Courtesy Florida Agricultural Experiment Station

Zinc deficiency of peach leaves

Crinkling, waving, and chlorosis of peach leaves as a result of zinc deficiency. The leaf at the right is normal.

Sommer and Lipman (291). Since that time all carefully controlled experiments have verified their results, and zinc has been accepted as one of the plant micronutrients.

The role of zinc within the plant is at present a matter of speculation, but some form of leaf chlorosis appears among other symptoms in all deficient plants thoroughly studied, indicating that zinc is related to the formation of chlorophyll in an undetermined way. Other symptoms associated with chlorosis and necrosis of the leaf, such as scant foliage, shortened internodes, and reduced fruit, are probably supplementary to insufficient leaf production. "Mottle leaf" of citrus, pecan "rosette," and "little leaf" or "rosette" of fruit trees are well-known diseases found to be caused by a lack of this element, and zinc deficiency seems to occur in some degree wherever citrus is grown.

Courtesy Florida Agricultural Experiment Station

Zinc deficiency in young peach tree

Characteristic symptoms of acute zinc deficiency in young peach tree: little leaf, crinkling, rosette, defoliation, and twig "dieback."

Zinc seems to be present in all soils in minute quantities, but conditions in some of these soils appear to make it unavailable or almost so. It becomes less available as the pH rises, and the critical point seems to be around pH 6 to 6.5. In some sandy soils, a zinc deficiency may be due to cropping out of naturally available zinc and failure to replace it through fertilization; while on heavier soils, zinc is frequently tied up by organic compounds (61). Organic fertilizers are higher in zinc content than inorganic fertilizers, and the increasing reports of zinc deficiency may arise from the reduced use of organic fertilizers and the increased use of inorganic fertilizers containing little or none of the element.

The content of zinc in the plant appears to vary to a considerable extent, depending on the amount available in the soil. In the general run of vegetables, amounts range from 1 part per million to 10 parts per million; but cereals and legumes contain from 10 parts per million to 50 parts per million. Ordinary forest-tree leaves have been found to contain from 2 parts per million to 240 parts per million (194). Robinson and Edgington (257) give several examples of common plants and weeds with inordinately high zinc contents obtained in unusual locations rich in the element. Also, there is the classical case of a certain violet (*Viola calaminaria*) taking up huge quantities of zinc from soils in the zinc industrial regions of Belgium. In this case, however, there is some question about zinc-dust contamination (257).

Zinc is found in all animal tissues, the amount in the human body being around 2.2 grams, or about one-half the iron content. The thyroid, liver, and pancreas contain the most, especially the thyroid. Livers of young animals have much more zinc than those of adults, suggesting a storage of the element in the young animal before birth, as is the case with copper and iron.

After repeated attempts by several investigators, a zinc deficiency was produced in experimental animals in 1935. It was found that the animals getting zinc lived longer and grew better than those on a diet containing little zinc. The rate of absorption of carbohydrates and proteins from the gastrointestinal tract is influenced by the concentration of zinc in the diet.

In zinc-deficient rats, a distinct delay in the tissue interval for absorption of both carbohydrate and protein from the gastrointesti-

nal tract has been proved. This delay leads to a decrease in the efficiency of converting food into body tissues.

Zinc has been found in the pancreas and also in all commercial preparations of insulin. As the zinc content of the pancreas in a diabetic person is one-half that in the nondiabetic, it has been suggested that part of the zinc in the pancreas may be concerned with the storage and utilization of insulin.

Chandler (63) and Camp (61) have recently discussed the theories of the action of zinc on plants; and the most complete bibliographies are found in Willis (321) and the compiled *Hunger Signs in Crops* (123), the latter volume containing colored illustrations of deficient and normal plants.

XIV. IODINE

A. *Early History of Iodine*

IODINE is probably the one trace element of which the public is dimly aware—not because people are interested in iodine other than as an antiseptic but because they have heard that iodine has something to do with goiter. Everybody knows of that affliction, which frequently makes its appearance as a tumerous condition of the thyroid and is dreaded by women who like to appear at social gatherings requiring *décolletage*.

Although the value of iodine to the plant is problematical, with most of the evidence on the negative side, its necessity for animals is unquestioned. It is a well-established fact that the incidence of goiter and cretinism is far greater in regions naturally deficient in this element than in regions in which the soil and water contain a sufficient amount. When present in the soil or water, iodine is easily assimilated by plants and readily obtained from them by animals.

Although goiter and cretinism have been recognized in human beings for centuries, their relation to iodine was not suspected until early in the nineteenth century. The public, with its traditional antipathy to new ideas, however, did not accept the fact until forced to do so by overwhelming evidence many years later.

Iodine was discovered in 1811 during the British blockade of France, when Napoleon was cut off from Chilean saltpeter for the

making of gunpowder. A nitrification plant was set up in which calcium nitrate was treated with the ash of seaweed to produce potassium nitrate. The nitrate oxidized the iodide present in the ash to iodine, which crystallized in the vats.

Following this discovery, various investigators obtained iodine from many sources: seaweeds, sponges, sea water, spring water, marine animals, water cress, and plants from various localities. The element was found in considerable amount in a number of mineral springs reputed to cure goiter. In 1820, the chemist Dumas collaborated with the physician Coindet in a careful study of the use of iodine in the treatment of goiter (182). Chatin, in 1850, systematically studied the distribution of iodine in France, and later advanced the hypothesis that the deficiency of iodine in certain countries causes goiter—suggesting that, by changing the water or by the use of wine, water cress, eggs, or sea salt, goiter might be prevented. Preparations of the thyroid gland were used four thousand years ago by the Chinese, and the use of burned sponge dates back to antiquity. However, despite the utilization of these substances in goiter cases and the work of Coindet and Chatin, the facts were accepted by very few persons, and goiter remained widespread throughout the world.

During the period 1873–95, Pasteur emphasized the germ theory of disease. So convincing were his arguments that the older chemical theories were neglected; and, because the germ theory was expected to explain everything, the medical profession fruitlessly hoped for the discovery of a germ that caused goiter. The general acceptance of iodine deficiency as the cause not only of goiter but also of cretinism came slowly with the study of the thyroid gland and the isolation of thyroxin.

B. *Goiter Incidence and the Geographical Distribution of Iodine*

The geographical distribution of iodine is roughly correlated with the incidence of goiter, but goitrous localities are so irregularly distributed that large-scale maps are necessary to show the details. Such maps have been prepared only for Switzerland, New Zealand, and the United States. In the United States, the greatest incidence of

goiter is in the Pacific Northwest, east of Montana and south in the mountains to Colorado. Goiter is also prevalent in parts of Michigan, Minnesota, and Wisconsin.

The least goiter is found in the Southern states and the coastal-plain areas of the Eastern Seaboard, regions known to have been submerged in the past. During the Permian period, an arm of the Pacific Ocean was cut off by the Rocky Mountains and made an inland sea covering parts of South Dakota, Nebraska, Kansas, Oklahoma, Texas, and New Mexico. This is a region of soils with high iodine content, and it is possible that much of the iodine was derived from evaporated sea water. The fact that the iodine content of various native rocks differs greatly explains local variations in the iodine content of soils.

The sea is the greatest source of iodine; and, as all salt deposits are the result of the evaporation of either sea water or the water of inland salt lakes, it is interesting to compare the per cent of iodine in the ocean and salt lakes with that in waters of deficient regions. Although analyses of samples from separate localities differ, an average of 20 to 50 parts per billion in ocean water would not be far from correct. Water from the Great Salt Lake has been found to contain 70 parts per billion. In comparison, water from Lake Superior taken at Duluth, Minnesota, contained only 0.01 part per billion, and the village supplies of several Michigan towns contained no determinable quantity of iodine.

Small amounts of iodine have been found in the air at different heights above the ground, this incidence being attributed to the evaporation from sea water, but the amount is so small that it is of little benefit. Sea water containing iodine is brought down from the atmosphere chiefly by the action of rain drops; but it has been estimated that at a distance greater than three miles from the ocean the effect is negligible so far as the addition of iodine to the soil is concerned.

c. *The Iodine Content of Plants*

Iodine has not been proved to be essential to plant growth, but most plants contain measurable amounts. Leafy vegetables absorb iodine readily, the amount depending to a great extent on the iodine

content of the soil on which they are grown (115, 169). Dietz (83) greatly increased the iodine content of leafy vegetables, and non-leafy vegetables to a less extent, by the application of twenty to forty pounds of potassium iodide per acre, without increase in yield. Scharrer and associates (265) fertilized pastures with potassium iodide, thus increasing the iodine in the grass and in the milk from cows that grazed the pastures. Although animals from both the treated and the check pastures were in good health, the former reproduced more freely and gave higher milk yields with longer lactation periods.

The iodine content in plants is consistently higher in nongoitrous regions where the iodine content of the soil is greater. For example, McClendon (182) showed that oats and cranberries from Minnesota and carrots from Oregon, both goitrous regions, contained 1, 0, and 0.3 parts per billion of iodine when compared with oats from Maine, carrots from California, and cranberries from Massachusetts, which contained 175, 170, and 100 parts per billion respectively.

Marine algae contain large amounts of iodine and have been used as a source of the element. Fish and other sea foods are rich in iodine and contain in the fresh state up to 1,000 parts per billion (307).

D. *Prophylaxis of Animals and Human Beings*

Animals absorb the iodides of sodium or potassium with extreme rapidity when taken by mouth. Iodine may also be absorbed from the skin and lungs. When iodine is deposited on the skin, it is absorbed and appears in the urine (316). The ability of the animal body to absorb iodine makes possible the treatment of a goitrous condition or prophylaxis against potential goiter.

For many years sheep raisers in Michigan prevented goiter in their animals by the use of crude salt containing traces of iodine, and, at present, use of it or of iodized salt is general by raisers of livestock in iodine-deficient regions. Refined salt has little value for goiter prevention as practically all of the iodine is lost in the process of refining.

The "hairless-pig malady" has been shown (131) to be occasioned by low iodine assimilation, which results in a goitrous con-

dition of both mother and young, but interferes more severely with fetal development than with normal development of the mother. The malady, most common in regions low in iodine, may be alleviated by the use of iodides in the feed of pregnant sows and prevented by the general use of iodine in the feed at all times.

In 1917, Marine and Kimball (197) conducted experiments in the schools of Akron, Ohio, by giving 2,110 school girls two grams of sodium iodide twice each year for three years. Only 5 have developed goiter, while 495 of the 2,305 girls not given iodine have developed goiter. The results were so striking that iodine prophylaxis for goiter was adopted in many parts of the United States, Europe, New Zealand, and India. The use of iodized salt is now general throughout the goiter region, and physicians have found that all adolescent and many adult goiters slowly decrease in size when iodized salt is used. Kimball (165) is of the opinion that the rapid disappearance of endemic goiter among school children in Michigan is one of the outstanding achievements in preventive medicine.

Rochester, New York, has increased the iodine content of its city water by the addition of 16.6 pounds of sodium iodide every day for two weeks, twice a year. Shortly after the applications had been made at the upper end of the reservoir, the iodine content of the water was raised from about 1 part per billion to about 5 parts per billion (182).

In spite of the proved value of the use of iodized salt, iodides in drinking water and other methods of inorganic-iodine intake as a prophylactic against simple and exophthalmic goiter, there remains a possibility of danger in indiscriminate use. It appears that in cases of toxic adenoma, where the thyroid is capable of producing abnormally large amounts of thyroxin, the continued use of foods or salt containing more than the minimum amount of iodine is dangerous because of the potential threat of hyperthyroidism. Kimball (164) concludes that there is no possibility of producing toxic adenoma in children by the continued use of iodine in amounts sufficient to prevent goiter and that there is no basis for the statement that iodized salt may induce hyperthyroidism in long-standing goiters.

Cameron (60), on the other hand, believes that the amount of iodine in iodized salt is greater than necessary for prophylaxis, and states that there is some slight evidence that a very small per cent

of nontoxic goiters may develop a hyperthyroid condition through the use of the salt. Eckstein (92) also warns of the danger of hyperthyroidism when iodine is used as a direct supplement to the diet but states that no danger exists when the iodine content of crops is raised by the use of iodine-rich fertilizers such as Kainit, superphosphate, and Chilean nitrate. Gaus and Griessbach (115) also recommend the use of iodine in fertilizers as the best means of obtaining iodine for the animal via the plant.

Turrentine (310), in recommending kelp in preference to inorganic salts of iodine, advances the opinion "that it is preferable that the body be permitted to secure its iodine from some natural vegetable carrier of the element by natural digestive processes of selection and elimination through a prolonged digestive period rather than from some chemical, highly soluble, and of high penetrative powers, against which the natural protective and defensive agencies of the body are not able to prevail." McHargue and associates (189) showed that plants may absorb relatively large amounts of iodine without producing any signs of toxicity and that it is a simple matter to increase the iodine content of forage crops and vegetables by adding potassium iodide to the soil. In this manner iodine is in organic combination and, therefore, in suitable form for assimilation by livestock and man.

Goiter and cretinism are unknown among the Japanese, the greatest users of kelps and other seaweeds. Jarvis, Clough, and Clark (155) recommend canned salmon as a convenient source of iodine in goitrous regions. There seems to be no doubt that a greater consumption of sea food, both plant and animal, would supply enough iodine to the system in an unquestionably harmless form, but the amount of such food available is insufficient to supply a small fraction of our needs.

E. *Conclusions*

Iodine is one of the most important trace elements so far as animals are concerned, a deficiency causing goiter in persons and animals, cretinism in persons, and a disease in hogs known as "hairlessness." The incidence of these diseases has been fairly well correlated with the relative amount of iodine in the food and water.

The history of the problem teaches that, although the treatment of goiter is not too satisfactory, the disease is one of the easiest to prevent.

Iodized salt is the most commonly used prophylactic; but there is evidence that, because of the danger of hyperthyroidism, it is preferable that iodine be taken into the body in the organic form. Iodine appears not to be essential to plant life—although when in the soil it is easily absorbed by plants, especially by leafy vegetables and forage. Iodine salts may easily be applied to the soil in fertilizers, and sufficient amounts will be absorbed to prevent the iodine-deficiency disease with little danger to those prone to hyperthyroidism.

Under investigation at the present time are methods of increasing the iodine content of man's food supply by adding the element to fertilizers for growing plants (189) and by enriching the diets of the dairy cow (253) and the egg-laying hen (23) through feeding iodine concentrates. Results show that enrichment is possible, the extent of increase in iodine content of the food being dependent upon the amount and kind of the iodine compound employed. Additional work should be undertaken to determine the relative value to animals of iodine in the organic and inorganic forms.

The literature on iodine, being so inextricably bound up with medical findings relative to goiter, is naturally very extensive. Several excellent reviews and bibliographies on the subject are available (60, 115, 182, 230, 238), including McClendon's exhaustive compilation in book form intended primarily for research workers (183).

XV. BORON

THE PRESENCE OF BORON in plants was discovered almost a century ago (319), its importance suggested in 1914 (48, 209), and its essentiality proved without doubt in 1936 (291). It is only recently, however, that its practical importance has been demonstrated.

Investigations prior to 1914 were marked chiefly by the detection of the element in plant tissue. During World War I, when American potash salts were used on a large scale for the first time, it was discovered that toxic amounts of borax were being added along with

Boron deficiency in alsike clover

The leaves on the left (A) are boron deficient; those on the right (B) are normal.

A boron deficiency in alsike clover makes its appearance as a brownish-red discoloration of the leaflets, which eventually become ragged and necrotic at the edges.

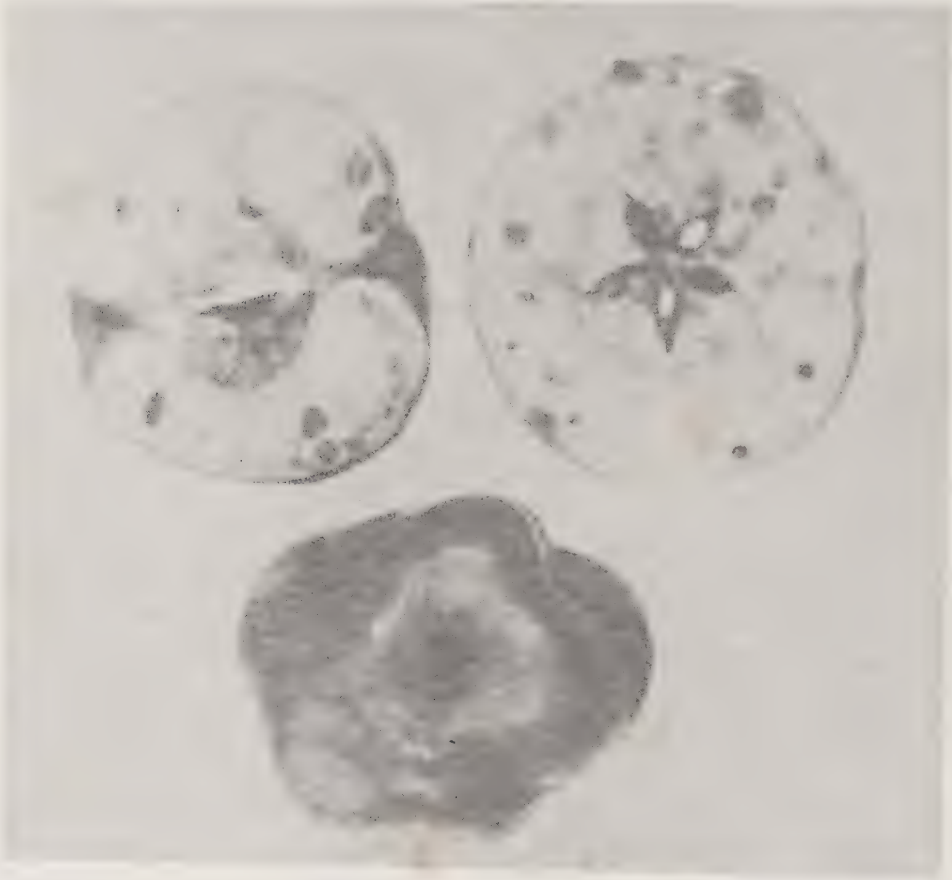
the potassium. The chemist soon overcame this difficulty by removing the borax from the potash salts, but undoubtedly the unfavorable publicity adversely affected research on the value of boron during the decade which followed.

Interest suddenly rose after 1931—possibly stimulated by the work of Brandenburg (47), who reported that heart rot of sugar beets was caused by boron deficiency rather than by an organism. Since 1931 the influence of boron on the growth and development of plants has been more extensively studied than that of any other element.

At present its fertilizer value is fully appreciated, and a deficiency of it is recognized as the causative agent for heart rot of beets, brown heart of turnips, cracked stem of celery, top sickness of tobacco, internal cork of apples, browning of cauliflower, and yellows

of alfalfa. Boron deficiency in many podzolic soils has been found within the past few years, and Whetstone and his associates (319) have pointed out three regions in the United States in which soils are likely to be deficient in this element: the Atlantic coastal plain; a region across northern Michigan, Wisconsin, and Minnesota; and the Pacific coastal region, including the Pacific Northwest.

The amount of the element necessary for the optimum functioning of plants is relatively low, and the range between boron deficiency and toxicity is narrow. In many plants, less than 0.01 part per million of boron in the soil solution will cause deficiency symp-



Courtesy Cornell Agricultural Experiment Station

Internal cork of apple (variety Fameuse)

A boron-deficiency symptom. Note the early-season form (rounded, hard, dry, brown spots with definite margins) and the late-season form (large, soft, light brown areas with indefinite margins).

Courtesy Cornell Agricultural Experiment Station

Leaf injury in apple from too much boron (variety McIntosh)

Note the fading of leaf-blade color, especially near principal veins, and in severe cases, the rolling of leaves, and the marginal scorching. The photograph was taken in July.

toms, while more than 1 part per million may be toxic; but as Brenchley, who pioneered in this work, points out (48), the limits of deficiency and toxicity are of little value unless correlated with external factors such as season, photoperiod, and the nature of the substratum in which the plants are grown.

The narrow range indicates that boron is not absorbed and held by soil colloids as are copper and zinc. This indication receives support from the fact that irrigation waters contain considerable boron, and deposits of borax occur in the evaporated residues of surface soil water in some arid regions.

The deficiency effects of boron vary with the type of plant, its age, and the conditions under which it is grown; but the meristematic tissue is most severely affected. Important indicative symptoms that may appear include death of the apical meristem, failure of young roots to develop, and hypertrophy of the cambium. These symptoms may be followed by a disintegration and discoloration of the phloem and ground parenchyma and, eventually, by a breakdown of xylem tissue, which blocks the conducting system (192).

It has been suggested for some years that boron functions in plants in conjunction with other ions, particularly calcium and potassium (52). The existence of such a relationship has now been well established (160, 224, 252), and more recently it has been shown that the nitrate and phosphate ions should be included in this category (32). However, the mechanisms involved in these relationships are not well known. Boron probably plays a part in the transportation and utilization of carbohydrates, and possibly is functional in protein metabolism.

Boron has been found in the tissues of various domestic animals and in milk and eggs (142). It is felt now that boron exists normally in very small amounts in all animals, being more common in species of marine origin; but little is known of its role in human nutrition, and no evidence has been presented to indicate its essentiality in the animal diet.

Probably because of the recent increasing interest in boron and the large number of physiological diseases attributed to boron deficiency, an unusually large number of reviews on the subject have been published (80, 107, 117, 158, 193, 211, 278).

XVI. MOLYBDENUM

THE NECESSITY OF MOLYBDENUM for plant growth was for a time uncertain because of the small amount required. Bortels (44) found that both molybdenum and vanadium promoted growth and nitrogen fixation of azobacter, and he assumed they acted as catalyzers. Garner (113), and later Steinberg (294), showed that this element is necessary for the growth of *Aspergillus niger* and important in nitrogen metabolism. Molybdenum as an essential element for higher plants was first demonstrated by Arnon and Stout in 1939 (22) and confirmed by Piper (243) the following year.

The amount of molybdenum required by plants is very small and the distribution of the element in soils so extremely wide that there is little chance of noticeable deficiency symptoms appearing under natural conditions, especially if the presence of molybdenum in the soil is demonstrable. In the laboratory, symptoms of molybdenum deficiency may be obtained only when the greatest care is taken to exclude this element from the nutrient medium. According to the investigations of Arnon and Stout (22), who used the water-culture method, molybdenum is not highly toxic to the tomato plant in comparison with other elements of a micronutrient character. A 10 parts per million concentration of molybdenum was required to produce easily observable injury.

A trouble referred to as "teartness," known for more than one hundred years to be definitely associated with certain pasture areas in England and not with others, has been established as a molybdenum toxicity. The trouble affects ruminants, particularly calves, and cows when fresh. The physical symptoms are extreme diarrhea, with consequent loss in weight and milk yield. In 1938, Ferguson and associates (102) reported studies of the herbage in the unhealthy areas, showing it to be high in molybdenum compared to that in normal areas. By feeding small amounts of soluble molybdates to cows, they produced the same symptoms noted in animals grazing on forage high in the element. Herbage from healthy areas averaged less than 5 parts per million on a dry-matter basis, while the content in samples from "teart" areas ranged from 30 to 80 parts per million. It was shown that a considerable part of the molyb-

denum fed was absorbed and excreted in the urine, but no clue was obtained to its specific action. No evidence has been found to indicate that the animal can use molybdenum in any form.

One review of molybdenum in relation to plant growth was recently published (140).

XVII. ALUMINUM

ALUMINUM has been found in the ash of all plants that have been examined. The amount varies greatly for different plants, and it is apparent from analytical results obtained that they possess considerable specific selective powers toward the element. From a trace, the amount may go as high as 6.2 per cent in the ash of certain pteridophytes (149). Some plants are apparently aluminum accumulators, and Hutchinson and Wollack (150) found such species to be especially common in the *Melastomaceae*, *Diapensiaceae*, and *Symplocaceae*. Except possibly in such accumulator species, aluminum seems to be of no nutritional value to the plant, as no deficiency diseases have been reported when it is lacking.

Several investigators (120, 173, 210, 287, 299) have reported beneficial effects from aluminum and indicated that it was necessary for the best development of the experimental plants with which they were working. Hutchinson (149) states that all of these experiments can be criticized on the grounds that gallium may be involved as an impurity in the aluminum salts used, and that they should be repeated with this possibility in mind.

The most important aspect of aluminum is its action, when present in excess in soluble form, as a limiting factor to the growth of certain plants. An extremely large amount of work has been done on this problem, which has been reviewed by Hardy (126) in 1926 and again by Hutchinson (148) in 1943. Rose (261) gives a critical review of the literature to 1929—not only on aluminum in nutrition but also on copper, manganese, and zinc. McLean and Gilbert (191) cite differences in the views of various workers regarding the toxicity of aluminum to plants, and it now seems that acid soils are unsuitable for some plants on account of the acidity (309) but that, in other cases, the increasing concentration of hydrolyzate-oxidate elements limits the plant growth (171).

Magistad (195) found that the solubility of aluminum in the soil solution at various reactions practically coincides with the curve for the solubility of aluminum in water at the same reactions. As the acidity of soil solutions decreases to the neutral point, the solubility of the aluminum decreases to almost nothing. When the acidity becomes greater than pH 5, the aluminum solubility increases rather rapidly until pH 4.5 is reached, at which point it increases very rapidly.

Phosphate treatments, liming, and large applications of decomposing organic matter reduce the aluminum toxicity of a soil (58). In the case of the lime treatment, it is assumed that a rise in pH causes less aluminum to go into solution, but in the other treatments the mode of action is not so clear.

Some investigators have determined that acid phosphate reduces the toxicity of aluminum salts by precipitating aluminum phosphate in the soil (216, 242), and others have found that the phosphate renders aluminum salts largely nontoxic by counteracting their injurious effects within the plant (58, 326).

Aluminum is frequently used as a soil amendment for the better growth of *Rhododendron* and other calciphobic ericaceous plants[1] (69, 70), but its favorable action here is considered to be in replacing the lime and thus increasing the pH of the soil.

The effect of aluminum in the production of blue flowers in *Hydrangea* has been the subject of many investigations—among the latest those of Allen (15, 16) and Chenery (64), who showed that the blue color is due to the formation of an aluminum complex of a delphinidine diglycoside. Chenery also gives a complete review of the subject to 1937.

Most of the aluminum taken up by herbivorous animals is apparently excreted with the feces, and the net result is an organism considerably poorer in aluminum than the food it has consumed. Although McCollum and his associates (185) concluded tentatively that "aluminum is not a constituent of either plant or animal matter," several investigators (110, 149) have shown that, whereas mammalian muscle is low in the element, the viscera may contain as much as 1 milligram per kilogram. The best general value for mammalian tissue is probably about 0.5 milligram per kilogram, repre-

[1] Members of the heath family.

senting about one-fortieth of the quantity of the element in the food.

Despite the low quantity of aluminum present in mammalian tissue and the negative results of all modern experiments in producing aluminum-deficiency symptoms in mammals, there is evidence (141, 148, 245) that aluminum is involved in the succinic dehydrogenose-cytochrome *C* system, which is the chief mechanism for oxidation of succinate in the mammalian body.

Although massive doses of aluminum in stoichiometric excess of the phosphate intake may cause a rachitic condition, there is little evidence that this would ever happen from the ingestion of human food prepared from aluminum-containing baking powders or cooked in aluminum utensils.

XVIII. SILICON

Silicon occurs in the ash of plants in greatly varying amounts, so that no general average may be given. It is especially abundant in the "scouring rushes" or *Equisetineae*, in grasses, and in the bark of trees. Silicon has been found to compose 71 per cent of the ash of *Equisetum telemantia*, and 51, 67, and 46 per cent, respectively, of the straw of barley, wheat, and oats (214). On the other hand, the ash of the stem and leaves of red clover and alfalfa contain only 2.7 and 9.5 per cent of silicon, respectively.

The large amounts of silicon present in many plants early led to the belief that it might be an essential element in the nutrition of these plants. However, the fact that they could be grown to maturity in the laboratory with only the trace of silica that resulted from the slight impurities in the nutrient cast doubt on this assumption. Attempts to obtain purified nutrients or water free from silicon have not been too successful; and, although the case for the need of silicon for plant growth seems strong, at present an unqualified statement of its indispensability cannot be made. For the same reason, it has not been conclusively demonstrated that the green plant can live without the slightest trace of silicon.

Much of the early work on this element had to do with its possible effect in strengthening the plant and, in the case of grains, in reducing lodging; but at present the effect of silicon in preventing

lodging has been largely discounted (249). Miller (214) presents a summary of the work on this subject.

Silicon is also thought to have an effect on phosphorus availability, but conclusive evidence may have to wait until it is finally determined whether silicon plays an independent role in the growth of plants. There is some evidence to indicate that plants grown in solutions deficient in silicon are less resistant to attacks from disease (234, 287); and it is supposed that the presence of siliceous material affords increased mechanical protection to the outside walls of the plant.

Many animal tissues contain silicon, and a compound of silica and carbohydrate has been found in urine (74), but there is no indication that the element has any function in animal metabolism.

Reviews on the role of silicon in plant nutrition have been published by Sreenivasan (293) and by Raleigh (249).

XIX. SODIUM AND CHLORINE

PRACTICALLY ALL of the sodium and the chlorine in the animal body enters in the form of sodium chloride and, for the most part, functions and is excreted in this form. Sodium chloride helps to maintain the acid-base balance of the body and is largely responsible for the total osmotic pressure of the extracellular fluids. Because a diminution of these fluids occurs with age, in the adult there is a proportionate reduction of sodium and chlorine, the only two elements to be so proportionately reduced.

The liberal use of sodium chloride also facilitates the formation of digestive juices, permitting a free flow of saliva, gastric juices, and other intestinal secretions. Life cannot be supported and growth cannot take place when the sodium and chlorine intake is too low; but, although sodium cannot be replaced by any other ion, chlorine may be replaced in part by bicarbonate ions formed from carbon dioxide (112).

Sodium is not essential to plant growth, but its presence has a marked effect on some plants. According to Miller (214), sodium may be able to perform one or more of the following roles, depending upon environmental conditions and the type of plant under con-

sideration: (1) It is a conserver of potassium, because less is absorbed by the plant when sodium is added; (2) it may, to a limited extent, replace potassium as a plant nutrient, as it can apparently perform certain functions of potassium but not all of them and, when applied to a potassium-starved plant, delays deficiency symptoms but does not prevent them entirely; (3) when applied to a soil that is deficient in potassium, it may liberate a certain amount of potassium which was absorbed by the soil and make it available for the plant, thus bringing about an increase in growth; and (4) in particular cases, it appears to act as an antidoting agent for certain toxic salts present in the medium in which the plant is growing.

Chlorine in many instances has a morphological effect upon the plants growing in the medium to which it is applied, but the manner in which the chlorides may bring about the response is not known, and all the explanations that have been put forth are purely theoretical. Plants will grow to a healthy maturity in a medium free from chlorine, indicating that the reaction of the plant when chlorine is applied is probably due to changed conditions in the mineral content of the soil and not to its direct action upon the plant cells.

The sodium and chlorine content of plants is low, but the salting of farm animals is a normal procedure, and it is unusual to find evidences of a salt deficiency under ordinary conditions. Such a deficiency has been noted, however, in pregnant and lactating farm animals and in working horses in warm weather (143); but these conditions, although affecting the health of the animals, are local and temporary, and may easily be remedied or prevented, hence do not constitute a serious problem.

XX. FLUORINE

Fluorine is widely distributed in rocks, soils, and waters, and is found in minute amounts in plants and animals. Some phosphate rocks contain up to 3 or 4 per cent of fluorine; and as much of this may be retained in fertilizers made from them, they are particularly significant in plant and animal nutrition. In addition to its association with phosphorus as fluorapatite, fluorine may be found as the fluoride of calcium (fluorspar) and of sodium and aluminum. It

also occurs in combination with silicates as topaz, tourmaline, and mica.

Fluorine has never been shown to be essential to plant life; in fact, the fluorine content of a plant is little changed by an increase in the fluorine content of the soil upon which it grows. The root is somewhat more affected than the remainder of the plant, which does not show an appreciable concentration unless the roots contain a relatively large amount of the element (29). Fluorine in the form of fluorspar or cryolite seems to have little effect on plants (273), but high concentrations of the more soluble fluorides have been found to be toxic to germinating seeds and their subsequent growth (219).

It seems safe to say that, in cases of chronic fluorosis in man and animals, the intake was not primarily in the food consumed, unless gross surface contamination with sprays or fluoriniferous soils took place. The results of fluorine analyses on foods bear out this assumption, and the analytical data available show that very few foods contain more than 2 parts per million on a fresh basis (217).

Fluorosis is generally caused by fluoriniferous waters, by the ingestion of fluoriniferous wastes, by the ingestion or inhalation of gases and dust containing fluorine, and, also, in animals, by the ingestion of fluorine-bearing phosphatic supplements to the ration.

The first signs of fluorine toxicity appear in the teeth, although the teeth do not acquire so high a concentration of fluorine as the bones. The skeleton apparently acts as a buffer in immobilizing the toxic effects of small amounts of fluorine; but with the continuation of too great an intake, calcification of the ligaments and tendons takes place, and eventually degenerative changes in the kidneys, liver, adrenal glands, heart, central nervous system, and finally the organs of reproduction (217).

Minute amounts of fluorine are distributed in normal animal tissues, especially in the bones, teeth, and skin. Several investigators have held the view that fluorine is an essential element in animal metabolism; but although various essential functions of the element in the animal have been proposed, no conclusive proof has been forthcoming. Attempts to raise laboratory animals on a diet as free from fluorine as possible have been uniformly successful; and, if the element is necessary, as has been claimed, the amount required

is no more than would be present in a largely synthetic diet containing purified ingredients.

Endemic dental fluorosis, or mottled enamel, in the human is ordinarily caused by the consumption of water containing more than 1 part per million of fluorine during the period of tooth formation. White opaque areas appear on the enamel, and later brown patches. A remarkable correlation exists between the fluorine content of the communal water supply and the index of dental fluorosis (78). The fluorine problem is chiefly concerned with the need for avoiding water containing too much of the element in order to prevent the occurrence of mottled enamel. In many communities this is difficult, for all available water is contaminated with fluorine. In the past few years several methods of treatment of water for the removal of fluorine have been investigated, most of them proving unsatisfactory. The Arizona Agricultural Experiment Station has developed a method of removal by filtration (283), through the use of specially prepared ground bone. This method, based upon the previously mentioned fact that fluorine has a chemical affinity for bone, has proved effective and practical for reducing the concentration of fluorine below the level that causes the dental disease.

The only beneficial effect of fluorine as it occurs in the domestic water supply is its value in the prevention of dental caries, or tooth decay. This paradoxical effect of the continued use of water containing 1 to 2 parts per million of fluorine has been established firmly by epidemical experimental studies (57, 71, 79). The use of such water, or other fluorine carrier, is the only known prophylactic treatment against this widely prevalent dental condition. Whether the effect is brought about by structural changes within the tooth (induced by absorption of fluorine by the tooth substance), by the bacteriostatic effect of this acquired fluorine, or by changes in the buccal environment is not known, but it is likely that several factors are operating.

Because of this prophylactic effect on dental caries, the treatment of public water supplies with fluorine, in regions where the content is low, has been suggested. Medical authorities point out, however, that such large-scale measures are inadvisable until much more evidence has been obtained and several small-scale but long-range experiments have been concluded.

Several reviews, either general or dealing mainly with the physiological effects of fluorine, have been published (118, 184, 239, 258, 260).

XXI. ARSENIC, LEAD, AND SELENIUM

ARSENIC, LEAD, AND SELENIUM are not essential to plants and animals and are poisonous to both in rather small quantities. However, the extensive use of lead arsenate in insect and weed control and the more recent use of selenium as an insecticide have raised important questions regarding their rate when added to the soil, and their possible influence on plants and on animals feeding on these plants.

Arsenic is present in all soils, varying from a few tenths of one part to more than 500 parts per million. Most soils contain less than 10 parts. The addition of large quantities of arsenates to the soil, directly or indirectly, in control of insect pests has caused a distinct arsenic problem in the cotton belt, in areas infested with the Japanese beetle, and in some commercial fruit orchards.

There is abundant evidence that the contamination of soils by arsenic lowers the yields of various crops. The amount of arsenic available to plants depends on the reaction of the soil and the quantity and nature of the clay or colloidal matter. Toxicity occurs at a much lower level of arsenic in acid, sandy soils than in heavier-textured soils, especially if the clay contains an abundance of iron, but in sandy soils the arsenic is more readily leached out. Soils contaminated with arsenicals have been found to retain most of the arsenic in the few inches at the surface.

The main problem is to get rid of the arsenic applied as sprays or insecticides or to render it noninjurious. For the latter purpose, the addition of lime to decrease the acidity or the application of hydrated ferric oxides appear to be the most practical remedies. Hurd-Karrer (147) has found that phosphate applications will reduce or prevent arsenic injury to plants where the type of soil will permit the phosphorus to remain available. There seems to be no danger to animals which feed on vegetation from soils high in arsenic, as the plants will be injured before accumulating enough to be toxic to the animals.

Lead is present in plants and soils in very small amounts, and under ordinary circumstances the quantity consumed by animals has no effect on health. However, since lead is a cumulative poison, small quantities which in themselves cause no harm may become dangerous when taken constantly. For this reason, the accumulation of lead in the soil from spray residues may be of sufficient magnitude to raise the lead content of food plants to a point where their ingestion in quantity would be dangerous.

Lead is "fixed" by the clay of the soil; and it would appear that the sulfate, sulfide, phosphate, and carbonate ions should render lead added to a normal soil so insoluble as to be inactive. Very acid soils, however, increase the solubility of the lead. In some Oregon orchard soils, it has been found that lead was not carried down below plow depth after the orchards had been sprayed with lead arsenate for twenty years.

Soluble lead compounds are toxic to plants except in very low concentrations. In some commercial apple orchards, the residues from lead-arsenate sprays have accumulated to such an extent that the green-manure crops can no longer be grown. It is supposed that arsenic is chiefly responsible for this condition, although lead may be a contributing factor.

Selenium is the only mineral element known at present which may be absorbed in sufficient quantities by plants used as food to make them dangerously toxic to animals. Selenium is toxic to many plants, but some species known to be selenium accumulators are able to absorb many times the amount that would be lethal to ordinary plants. The average selenium content of these accumulators, almost all of which are legumes in the genus *Astragalus*, is about 800 parts per million, and the highest is 15,000 parts per million (305). In contrast, wheat from the same soils averaged less than 5 parts per million of selenium. Seleniferous soils are widely distributed in the semiarid regions of the western half of the United States, where the rainfall is insufficient to leach out water-soluble selenium compounds.

Two somewhat different forms of selenium poisoning in livestock are known—the chronic and the acute—both of which are characterized by similar pathologies. The toxicity of selenium is markedly reduced when the diet contains a high proportion of pro-

tein, and arsenic compounds also tend to protect animals against its toxic action.

Some insects are very sensitive to selenium and are killed by concentrations in the plant so low that they do not injure the leaves or other organs. This fact provides a means of controlling certain noxious insects by soil treatments and makes less necessary the use of insecticidal sprays, especially in the greenhouse.

Experiments have been conducted on the use of selenium in this manner as an insecticide and on the residual effects of the element on the edibility of vegetables grown in the soil thus treated (165a).

A number of reviews and comprehensive treatments of selenium and the problems connected with it have recently been published (166, 221, 222, 223, 232, 284, 305, 306).

XXII. HUMAN NUTRITION

A LARGE PART of the literature dealing with nutrition concerns domestic animals and cultivated plants, practically all of which may be considered in terms of human nutrition. It is not possible to separate the problems of increasing the productivity of our farms, raising the biological value of our crops, keeping our domestic animals in good condition, and maintaining the general health of our people. They are all parts of one larger problem. Mineral deficiencies in human beings result from the consumption of inadequately fortified food—vegetable, animal, or both. The animal cannot be healthy without receiving nutritious forage; and the forage, to have the proper quality, must come from productive soil containing the needed mineral constituents. It may be seen, therefore, that regardless of what general phase is considered, the nutritive value to us is the final consideration. There is also another part of the problem that has received little attention and is economic in nature—creating a public demand for a superior quality of food. This may be the most difficult phase of all when we consider how much a nation, a section, or even a family is set in its food habits.

The most widespread deficiencies in human beings and farm animals usually attract little attention and are not manifested by clinical symptoms. Under extreme conditions and in the laboratory,

nutritional-deficiency symptoms are quite apparent but may be exaggerated beyond their rightful economic importance. The slight deficiencies evidenced by a decrease in the production of work, wool, or human food are less apparent but far more important.

On marginal farms in many parts of the range country, cattle and sheep are seldom able to eat sufficient forage to meet physiological needs for optimum growth; and, in some parts of the United States, many people are undernourished even though their appetites are satisfied.

When pastures are short, animals may not be able to gather enough food in the time available; but in this case the need for additional food is usually apparent to the owner. On pastures of relatively low nutritive value it might appear that sufficient forage is available; but it not only may be too dry and fibrous to supply sufficient energy, it also may be deficient in protein and mineral content. Animals feeding on marginal protein-deficient pasturage will grow slowly, will produce little milk, and, in the case of beef cattle, will fatten poorly if at all.

Young farm animals which suckle their dams for various lengths of time do not suffer from a protein deficiency during the early months of life unless they are removed from the parent at too early an age. The feeding of leguminous hay, silage, or grain, or the use of leguminous pasturage usually furnishes ample protein. There is a tendency for the protein content of herbage to be lower in areas of limited rainfall than where the rainfall is greater, but wide variations are shown (144). The protein content of forage is higher in the spring than later in the season, and pastures and ranges sufficient in the spring may become deficient in the summer and autumn.

Energy (or carbohydrate) and protein deficiencies are not ordinarily associated with any particular part of the country, as certain mineral deficiencies may be, but are found for the most part in areas where the general level of agricultural endeavor is low. Almost without exception, the health of the livestock is correlated with the health of the people who raise them; and sleek, well-nourished cattle or healthy, equally well-nourished children are not found on worn-out, eroded farms.

As has been stated before, extreme conditions attract attention, and for that reason are perhaps less of a problem than the marginal

cases which are far more numerous. For example, people living in the iodine-deficient region around the Great Lakes are aware of this deficiency, and a supplement of potassium iodide is added to all salt consumed by them or by their livestock, almost without exception (205). But there are also marginal areas in which the deficiency is not extreme enough to produce frequent trouble, and only occasionally is there some difficulty (136). The people and their livestock in these marginal areas should receive an iodine supplement, but the amount used in the Great Lakes area would be excessive, and none at all would be required in many cases. The best method of insuring an adequate supply in these regions would be to add it to the fertilizer for food plants in the areas (189).

It would appear that, in some cases at least, the mental and physical lethargy of a portion of our rural population is due primarily to a serious mineral deficiency rather than to a combination of hookworm and malaria, the once common concept. In certain part of Florida it was found that on soils overlying rock phosphate subsoils only 3 per cent of the children had anemia; but near by, where this soil condition was not present, 96 per cent of the children had anemia. Using the prevalence of salt-sick cattle as a measuring stick for the nutritional wealth of the soil, investigators found that the anemia was definitely linked to the soil in a most striking manner. From 52 to 96 per cent of the children were anemic in those counties with a deficient soil; but when the soils were sufficiently rich in minerals to prevent the cattle from being salt-sick, at most only 23 per cent of the children were anemic or, in some cases, none at all.

Domestic animals usually show nutritional deficiencies before the families of their owners. The reason is apparent. Domestic animals are in closer contact with the indigenous food and crops than human beings of a region; consequently, the deficiencies will appear first in the animals subsisting on these crops. Moreover, the relatively short life span and the fast rate of growth of animals more quickly expose nutritional troubles, which in man may remain concealed for a time.

The animal serves as a screen, although by no means a perfect one, so that persons who are heavy consumers of eggs, dairy products, and red meat are less likely to be troubled by mineral defi-

Courtesy Farm Security Administration

Human health goes with the soil and its fertility

ciencies than those whose consumption of these products is limited. Although it is possible to obtain eggs and milk of inferior mineral values, the hen or the cow, under ordinary circumstances, will fall off in production before the eggs or milk begins to evidence inferior nutritional value. Unfortunately, from the point of view of our national health, dairy products and eggs are not a cheap source of food; and many families, especially in the low-income brackets, do not receive a sufficient amount. Such families frequently live almost entirely on food of the lowest cost per pound—a diet generally far too high in carbohydrates, frequently low in protein, and usually much too low in minerals and vitamins.

It is also true that a rural population in a deficient region, subsisting almost entirely on food grown locally, is far more apt to be troubled with mineral starvation than the urban population of the same region who obtain part of their food from other sections of the country.

There is perhaps no portion of the globe in which the inhabitants can boast of a freedom from all forms of nutritional deficiency. One

such deficiency, rickets, commonly recognized as an affliction of childhood and young, growing animals and caused by the lack of vitamin D, calcium, phosphorus, or combination of the three, may be considered in itself nearly universal. Anemia also is widespread and has been ranked by medical men second in rate of occurrence to rickets. The considerable difference in incidence of defects of the heart, the vascular system, and the teeth and bones among young men drafted for military service from different sections of the country can scarcely be attributed to any other factor than a difference in the mineral and vitamin content of their food in general, taken over a period of years (262).

Numerous experiments, some of which have been cited, have shown that soil treatments may increase the mineral and nutritive value of crops, changing them from mere producers of energy to food of real worth; and that animal-feeding methods may make possible the production of meat, milk, and eggs of superior food value. Nevertheless, in spite of this evidence, little has been done towards improving the nutritive worth of our crops and animal products.

Foods lacking the health factors, yet fresh and attractive in appearance, bring the same price on the market as the more nutritive foods; and little if any effort has been made by public-health organizations to provide laws governing the sale of such products. The producer of edible but inferior food of low mineral and vitamin content feels at present no social responsibility for increasing the value of his product, nor is he handicapped in its sale. The consuming public as individuals have no way of distinguishing the superior food from the poor, and for the most part are completely at the mercy of the growers and purveyors who, by reason of ignorance or for economic gain, grow or market inferior products.

People of greater purchasing power usually fare better than those of limited means, chiefly because they are able to consume a greater variety of food, some part of which will contain the minerals lacking in another. On the other hand, people of limited means may confine themselves to a narrower range of choice and are less likely to purchase foods high in mineral and vitamins but low in energy-producing qualities.

It cannot be expected that the producer will market a superior grade of food requiring added effort on his part unless the public

demands it, which thus far it has not done, or unless he sees the possibility of economic gain by advertising a superior product to a discriminating few.

The need for improved animal and vegetable food products is indicated, but the unresponsive public should be made aware of the necessity for nutritional as well as energy-producing food. To do this is probably the most difficult problem of all. Of what use is the production of a superior product if there is no demand for it? We are well aware of the preference for devitalized white over graham flour and for polished over brown rice. Many housewives yet boil cabbage and other vegetables several hours, pouring off all of the liquor and serving the fibrous residue as food. Many families wonder why their children have pellagra when they have plenty of corn pone and salt back to eat.

We are fortunate in this country that the two minerals needed in the largest quantities, calcium and phosphorus, are plentiful and cheap. Workable deposits of phosphates are found in nine states, and we have two-thirds of the world's reserve of high-grade phosphate rock. We also have limestone to last indefinitely, and it has been estimated that there is enough potash to supply our needs for many years to come. Our supply of the microelements is also ample.

We are protected by law against the indiscriminate flooding of the market with harmful drugs; but we are not at present protected, or even warned, against inferior food. The slow process of education may have to provide the best solution, followed by a gradual development of legislation requiring a differentiation between a superior and an inferior quality of food.

We should create a public realization of the need for superior food products. We should show the producer the possibility of economic gain through the production of a food superior in vitamins and minerals, and we should make sure that such food commands a price corresponding to its nutritive value rather than to its bulk.

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